Effects of transmission line compensation and power factor correction on harmonic propagation

Robert Douglas Kingston

University of Nevada, Las Vegas

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Effects of transmission line compensation and power factor correction on harmonic propagation

Kingston, Robert Douglas, M.S.E.
University of Nevada, Las Vegas, 1994

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EFFECTS OF TRANSMISSION LINE COMPENSATION AND POWER FACTOR CORRECTION ON HARMONIC PROPAGATION

by

Robert Douglas Kingston

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering
University of Nevada, Las Vegas
May, 1994
The thesis of Robert Douglas Kingston for the degree of Master of Science in Electrical Engineering is approved.

Chairperson, Dr. Yahia Baghzouz, Ph.D.

William Brogan
Examiner Committee Member, Dr. William Brogan, Ph.D.

Peter Stubberud
Examiner Committee Member, Dr. Peter Stubberud, Ph.D.

Graduate Faculty Representative, Dr. Shashi Sathisan, Ph.D.

Dean of the Graduate College, Dr. Ronald Smith, Ph.D.

University of Nevada, Las Vegas
May, 1994
ABSTRACT

This thesis addresses power quality at two different levels, transmission and utilization. Harmonics injected at these levels can severely degrade the performance and long term reliability of the power system.

At the utilization level, a typical industrial power system configuration that requires power factor capacitors and tuned harmonic filters for reactive power compensation and harmonic control is analyzed. The resonant conditions for a given power factor correction or harmonic frequency are determined directly from the roots of a quadratic expression. This formulation allows a quick evaluation of the power factor range with excessive harmonic levels and reveals the effect of tuned reactors on the resonant frequencies.

At the transmission level, a method for analyzing series capacitor placement on long transmission lines to improve line loadability is described. The influence of the compensator on harmonic current propagation and circuit resonant frequencies is investigated. Computer simulations are performed on an actual 345 kV, 238 mile line.
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CHAPTER 1

Introduction

Power quality is an increasing concern in electrical power systems. Nonlinear loads, ranging from industrial variable speed motor drives to consumer electronics, are a rapidly growing component of the total electrical utility system's demand. These nonlinear loads inject harmonic currents into the power system that cause additional system stress and possible component failure. Concurrently, there is an escalating need for additional electric power. To improve power system capacity, many schemes are utilized that employ various types of compensation devices. The interaction of the injected harmonics with the compensated power system results in resonance conditions that further degrade system performance and lead to component failures. This thesis addresses the problem at two different levels within a power system, transmission and utilization.

At the utilization level, industrial power systems are often characterized as large consumers of reactive power and significant generators of harmonics because most of the load is composed of induction motors and static power converters. Over the past few decades, there has been a trend toward more applications of solid-state devices and power factor correction in industrial power systems. These events were triggered by the fact that static power converters are very efficient and utility rates are structured to encourage high power factors. This combination, however, often results in intolerable voltage and
current waveform distortion due to resonance conditions that may occur at or near characteristic harmonic frequencies [1].

Several methods have been suggested to mitigate harmonics including sophisticated devices such as series or shunt active power filters [2] - [4]. At present, tuned passive filters are the most widely used because of their low cost and simplicity. A common practice is to add a tuning reactor in series with an existing power factor capacitor. This shifts the resonant frequency from the characteristic harmonic frequencies and provides a short path for the lowest order harmonic, such as the 5th, that often dominates the frequency spectrum [5].

In cases where power factor correction capacitors exist at several busses within the system, there will be multiple resonance frequencies because each power factor capacitor can cause an additional resonance frequency. Consequently, a single LC compensator may not be sufficient to reduce harmonic magnitudes to acceptable levels and a resonance condition may still occur within the desired power factor range.

In Chapter 2, a typical system is analyzed where it is desirable to install power factor capacitors and tuned harmonic filters for reactive power compensation and harmonic control.

At the transmission level, long extra-high voltage AC transmission lines can carry limited power, often well below their thermal ratings, due to their significant inductive and capacitive reactances. As a consequence, series and shunt compensators are used to artificially reduce the line reactances to improve power transfer capability, system stability, voltage control, efficiency and transient voltage reduction. The recently adopted National
Energy Policy Act opens markets for more retail wheeling in North America and calls for an increase in the transfer of power. Hence, it is expected that transmission line compensation will find more application in the future.

Another change that has long been developing in the electric utility system is the ever-increasing use of power electronics devices in a wide range of electric loads. This nonlinear equipment injects high frequency harmonic currents into the transmission system. It is known that a harmonic current and resulting harmonic voltage can be magnified considerably, causing a variety of operational problems if resonance occurs at one of the harmonic frequencies. For this reason, a recommended limit for each harmonic voltage is set to 1% of the fundamental in transmission systems above 138 kV [5].

In compensated transmission lines, the harmonic current propagation and magnification is expected to depend upon the size and location of the compensator. Furthermore, the harmonic currents at some points in the line can exceed those measured at the line terminals by over one order of magnitude.

In Chapter 3, a method for analyzing series capacitor placement on long transmission lines to improve line loadability is described. The influence of the compensator on harmonic current propagation and circuit resonant frequencies is investigated through computer simulation.
CHAPTER 2

Power Factor and Harmonic Compensation in Industrial Power Systems with Nonlinear Loads

This Chapter analyzes a typical industrial power system configuration with two step-down transformers, one feeding nonlinear loads (adjustable speed drives), and another feeding linear loads (induction motors with no solid-state control devices) as shown in Figure 1 [6]. Bus 2 represents the so-called point of common coupling (PCC) between the industrial power system and the utility system.

The objective is to determine the values of reactive power compensators $C_1$ and $C_2$ to improve the low power factor, reduce the voltage total harmonic distortion ($VTHD$), and reduce harmonic currents injected into the utility system to acceptable limits recommended by the IEEE Standard 519 [5]. Note that the reactive power requirement for such loads depends on the motor operating speeds and torque, but given the sufficiently large number of these loads, a uniform kVAR requirement can be assumed due to diversity.

The research is composed of three sections. The first section covers the base case where the system response is analyzed with no compensators so that the harmonic currents injected at the PCC and the $VTHD$ at all three busses can be determined. In the
Figure 1 - Single Line Diagram
(typical industrial power system)

1:1 Isolation Transformer
1.1 MW @ 0.8 PF (lag)
second section, the system response is reexamined after installing power factor capacitors at busses 1 and 2 for reactive power compensation. The resulting harmonic magnitudes are then computed at different power factors. The two resonant frequencies caused by these capacitors are calculated by solving a quadratic equation rather than performing a frequency scan. Finally, in the third section, the latter process is repeated after adding one or more (if required) tuned reactors in series with the capacitor at bus 1 until the harmonic distortion levels are brought within the recommended limits.

2.1 ASSUMPTIONS

In order to simplify the analysis, the following assumptions are made:

(a) The system is balanced, hence, only the characteristic harmonics of positive and negative sequence are present.

(b) The resistance is ignored since there is little resistive load in industrial systems. It is important to keep in mind that the resistance provides damping which reduces the magnitude of harmonics; hence, the study is more conservative.

(c) The utility system impedance consists primarily of the substation transformer leakage reactance.

(d) For simplicity, the power factors at busses 1 and 3 are to be maintained at the same value.
2.2 COMPUTER SIMULATION

2.2.1 Uncompensated System

Figure 2 shows the equivalent circuit of the example system at a harmonic frequency of order \( n \). The induction motors are represented by their short-circuit impedance that is dominated by the leakage reactance \([5]\), while the adjustable speed drives are represented by harmonic current sources with magnitudes given by Table I \([6]\).

<table>
<thead>
<tr>
<th>( n )</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>17</th>
<th>19</th>
<th>23</th>
<th>25</th>
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</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>24</td>
<td>11</td>
<td>7.5</td>
<td>7.5</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Bus 2</td>
<td>10.6</td>
<td>4.8</td>
<td>3.3</td>
<td>3.3</td>
<td>1.8</td>
<td>2.2</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Max*</td>
<td>7</td>
<td>7</td>
<td>3.5</td>
<td>3.5</td>
<td>2.5</td>
<td>2.5</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*IEEE-519 recommended limits (based on the system size \( I_{sc}/I_L = 33 \)).

The fundamental frequency reactances when referred to the low-voltage side are \( X_n = X_{sc} = 0.00575 \) ohms, \( X_m = 0.05 \) ohms, and \( X_s = 0.0023 \) ohms.

Harmonic currents flow from the nonlinear loads to the lowest impedance, usually the utility source which is generally much lower than the parallel path offered by the loads. In the circuit under consideration, the path of the utility source has an impedance that is only 4% of the load path impedance. The bus voltages at the \( n \)th harmonic frequency are calculated by the product of the injected harmonic current, the driving point impedance, and transfer impedance:

\[
V_1^n = Z_{11}^n I^n, \quad V_2^n = Z_{12}^n I^n, \quad V_3^n = Z_{13}^n I^n \quad (1)
\]
Figure 2. Equivalent Circuit of System
(at harmonic frequencies)
The harmonic current injected into the utility system is simply computed by:

\[ I_n^s = \frac{V_2^n}{nX_S} \]  

(2)

Where \( n \) is the harmonic order.

The impedances in (1) are easily derived from Figure 2, and their frequency variation is shown in Figure 3. Note that the curves are plotted in a logarithmic scale, which translate into straight lines when a linear scale is used. The corresponding currents injected into the utility supply are shown in Table I along with the recommended limits. The resulting voltage total harmonic distortion (VTHD) at busses 1, 2, and 3 are 6.7%, 1.9% and 1.7%, respectively.

Three quantities are considered excessive according to IEEE Standard 519 [5]; namely, the 5th and 25th harmonic currents injected into the system, and VTHD at bus 1. The utility supplier is more interested in the first two violations since bus 1 is within the plant and the voltage distortion at the PCC is well within limits.

### 2.2.2 Compensated System with Power Factor Capacitors

The amount of reactive power compensation depends on the economics of compensation with regard to the utility rate structure. A given rate structure may or may not result in an economical unity power factor. In this simulation, the system performance is evaluated through a power factor ranging from its initial value to unity. Further, the power factor (PF) refers to the displacement power factor, the power factor at fundamental frequency, since it is the quantity that is usually specified instead of the total power factor. Given the load \( P_l \) (kW) at bus 1 with initial power factor \( PF_0 \), let the
Figure 3 - Impedance vs. Frequency
(no compensation, PF = 0.80 lagging)
desired power factor be \( PF \). Then the required kVAR from the compensator is determined by:

\[
Q_{c1} = \sqrt{(P_1/PF_0)^2 - P_1^2} - \sqrt{(P_1/PF)^2 - P_1^2}
\]

(3)

and the corresponding capacitive reactance is calculated by:

\[
X_{c1} = V^2/Q_{c1}
\]

(4)

where \( V \) is the line-to-line bus voltage in kV. From assumption (d), the capacitive reactance \( X_{c2} \) that will provide the same power factor at bus 3 is related to \( X_{c1} \) by:

\[
X_{c2} = \alpha X_{c1}
\]

(5)

where \( \alpha = Q_{c1}/Q_{c2} \). Herein, \( Q_{c2} \) is calculated by (3) after substituting \( P_1 \) at bus 1 by \( P_2 \) at bus 3. The presence of capacitors will have a dramatic effect on the impedances seen by the harmonic currents. This can make impedances very large (parallel resonance) or very small (series resonance) at some frequencies. Parallel resonance is of great concern because it increases the harmonic voltage levels.

A common method to determine the resonance frequencies resulting from the two capacitors at busses 1 and 3 is to evaluate the impedances over a wide range of frequencies using a time-consuming procedure called frequency scanning. Another alternative utilizes root locus techniques to identify the poles and zeros of the operational impedances. In the system under study, the poles can be computed analytically by solving for the zeros of the denominator common to the driving and transfer impedances in (1). This denominator has been derived and found to be a quadratic polynomial of both harmonic order \( n \) and capacitive reactance \( X_{c1} \). For a given power factor, and hence, capacitive reactance, the above polynomial is of the form \( an^4 + bn^2 + c \) where,
\[ a = X_m (X_{l1}X_1 + X_sX_{l2}) \quad (6) \]

\[ b = X_{c1} (X_{l1}X_3 + \alpha X_sX_2 + X_mX_1) \quad (7) \]

\[ c = \alpha X_{c1}^2X_3 \quad (8) \]

with \( X_1 = X_s + X_{l2} \), \( X_2 = X_m + X_{l2} \), and \( X_3 = X_s + X_{l2} + X_m \).

For illustration purposes, let the desired power factor at both busses be \( PF = 0.95 \). The corresponding capacitive reactance \( X_{c1} = 0.496 \) ohms. Substituting this value in (6) - (8) and solving the quadratic equation yields \( n = (6.97, 9.16) \), indicating that the resonant frequencies are 418.2 Hz and 549.6 Hz respectively. To verify these values, a frequency scan is performed on \( Z_{l1}, Z_{l2}, \) and \( Z_{l3} \) as shown in Figure 4. These impedances become very large at the two frequencies calculated directly above.

Capacitor sizes causing resonance for a given harmonic order can also be computed directly. In this case, the same polynomial above is rewritten with \( X_{c1} \) being the variable, i.e., \( a \, X_{c1}^2 + b \, X_{c1} + c = 0 \), where:

\[ a' = \alpha X_3 \quad (9) \]

\[ b' = n^2(X_{l1}X_3 + \alpha X_sX_2 + X_mX_1) \quad (10) \]

\[ c' = n^4X_m(X_{l1}X_1 + X_sX_{l2}) \quad (11) \]

For example, the two values of capacitive reactance that cause resonance at the seventh harmonic, found directly from (5) with \( n = 7 \), are \( X_{c1} = (0.520, 0.319) \) ohms and \( X_{c2} = (0.486, 0.288) \) ohms. The corresponding power factors are \( PF = (0.940, 0.993) \) respectively. These results are validated by the plots of the driving and transfer impedances at the 7th harmonic frequency in Figure 5. Figure 6 combines the results of Figures 4 and 5 by displaying the two resonant frequencies that occur at various levels of
Figure 4 - Impedance vs. Frequency
(with compensation, PF = 0.95 lagging)
Figure 5 - Impedance vs Power Factor
(7th harmonic - 420 Hz)
Figure 6 - Resonant Frequency vs PF.

(effect of capacitive reactance)

---

- \( XC1 = 0.319 \text{ ohms} \)
- \( XC1 = 0.520 \text{ ohms} \)

Resonant Frequency (Hz)
power factor, and Figure 7 shows the variations of the voltage total harmonic distortion \( VTHD \) at all three busses. Assuming that the rate structure encourages a load power factor \( PF > 0.90 \), then the \( VTHD \) at busses 1 and 3 are considered excessive for all desired power factor values, while the \( VTHD \) at bus 2 is violated over two intervals, \( 0.92 < PF < 0.95 \) and \( PF > 0.99 \). The 5th harmonic current injected into the utility system is excessive throughout the power factor range, and the 7th harmonic current level is acceptable only for \( PF > 0.99 \). These results call for the installation of tuning reactors.

### 2.2.3 Compensated System with Power Factor Capacitors and Tuning Reactors

Since the 5th harmonic current injected into the utility supply is excessive for all capacitor values that result in \( PF > 0.9 \), a logical step, as recommended in [5], is to install a tuning reactor in series with the capacitor installed at bus 1. The current carrying capacity of the reactor should be at least equal to that of the capacitor. The LC circuit should be tuned to provide a short circuit path for the 5th harmonic, or the fundamental frequency inductive reactance is set to 4% of the capacitive reactance \( (X_c = 25X_L) \). The resulting power factor will be slightly higher with the LC compensator than with the power factor capacitor by itself. Hence to keep the same power factor, the capacitive reactance has to be increased by a factor as indicated by:

\[
X_{c1} = \frac{V^2}{0.960Q_{c1}} \quad (12)
\]

where \( Q_{c1} \) is calculated from (3). Consequently, the value of \( \alpha \) in (5) will decrease by 4% causing a slight deviation in the roots of the expressions directly above (6) and (9). The
Figure 7 - Voltage THD vs Power Factor
(without Harmonic Filtering)

Pow | Power Factor (lagging)
--- |-----------------------
0.8  | ---
0.85 | ---
0.9  | ---
0.95 | ---
1    | ---

Bus 1 — Bus 2 — Bus 3

1E0  | 1E1
1E2  | 1E3
1E4  | ---

(%) THD

---
resulting $VTHD$ variations with power factor are shown in Figure 8. Note the dramatic difference when compared to Figure 7. However, the voltage distortion ($VTHD$) is still unacceptable when $0.97 < \text{PF} < 0.98$. Further, the 7th harmonic current injected into the utility supply is also above the recommended limit in the same power factor range.

To correct this problem, another LC compensator tuned to the 7th harmonic is required. Hence, the capacitor at bus 1 is to be composed of two components. Let the two components be equal in size, each having a capacitive reactance $2X_{c_1}$ at fundamental frequency. The 5th and 7th harmonic tuning reactors should have an inductive reactance of $X_{L_a} = 2X_{c_1}/25$ and $X_{L_b} = 2X_{c_1}/49$, respectively, at the fundamental frequency. The resulting total capacitive reactance that provides the same power factor as before is:

$$X_{C1} = \frac{V^2}{0.9697Q_{c1}} \quad (13)$$

The additional reactor will have a small effect on the resonant frequencies determined after the installation of the 5th harmonic filter. The results shown in Figure 9 indicate the $VTHD$ at all busses are well within the acceptable limits as long as the power factor is above 0.90. Thus, the harmonic currents injected into the system are also found to be acceptable.
Figure 9 - Voltage THD vs Power Factor (with 5th and 7th Harmonic Filters)
CHAPTER 3

Series Capacitor Placement on Transmission Lines with Slightly Distorted Currents

Various combinations of series and shunt compensation schemes have been studied in terms of system efficiency [7] and voltage stability [8]. Recently, significant effort has been dedicated to developing advanced series compensators (ASC) in which the compensator's impedance can be adjusted continuously using fast power electronic switching devices [9].

In this research, only the classical series static capacitor compensator is considered because steady-state performance during heavy load conditions is of primary interest. The shunt reactors that are connected during light load conditions to absorb reactive power and reduce over-voltages can alter the resonant frequencies of the network. The objective is to investigate, through computer simulations, the effect of series capacitor size and location on practical line loadability, practical maximum power transfer, current harmonic propagation, and resulting harmonic voltage magnitudes.

A transmission line model is presented at both power frequency and harmonic frequencies. The model is altered to include the series compensator. Line loadability along
with the terminal harmonic voltages and currents are derived in terms of capacitor size and location. The model is then applied to an actual 345 kV, 238 mile long transmission line via computer simulation.

3.1 ASSUMPTIONS

Assumptions made in the following analysis include:

(a) The sending end terminal is connected to a stiff source with zero internal impedance; hence, voltage at that end is known and fixed (while the receiving end voltage depends on the load current).

(b) The circuit is balanced at all frequencies and the harmonic content of the receiving end current is known.

(c) The frequency variation of the line resistance and inductance are ignored.

(d) For optimal efficiency the series compensator must be distributed at several points along the line; however, for practical and economic reasons the compensator is concentrated at one point.

3.2 UNCOMPENSATED NETWORK

3.2.1 Network Model at Power Frequency

Figure 10(a) shows a transmission line of length L connected to a stiff generating source at the sending end and to a $P + jQ$ load at the receiving end. The sending end voltage and current are expressed in terms of the receiving end voltage and current as follows [10]:
Figure 10 - Transmission Line Circuit

(a) @Power Freq. (b) @Harmonic Freq.
\[ V_S = A_L V_R + B_L I_R \quad (14) \]
\[ I_S = C_L V_R + A_L I_R \quad (15) \]
where,
\[ A_L = \cosh(\gamma L), \quad B_L = Z_C \sinh(\gamma L), \quad C_L = \frac{1}{Z_C} \sinh(\gamma L) \quad (16) \]
and,
\[ \gamma = \sqrt{z^2 y}, \quad Z_C = \sqrt{z/y} \quad (17) \]

Herein, \( z \) and \( y \) are the series impedance and shunt admittance per unit length, respectively. Note that the above formulae involve complex numbers except for the receiving end voltage (since \( V_R \) is chosen as the reference with zero angle). The receiving end voltage is related to the receiving end current by:
\[ I_R = S^*/3V_R = \frac{P - jQ}{3V_R} \quad (18) \]
Substituting (18) in (14) results in:
\[ V_S = A_L V_R + B_L S^*/3V_R \quad (19) \]

By knowing the complex power at the load side and the magnitude of the sending end voltage, one can easily compute the receiving end voltage \( V_R \) by equating the magnitudes of both sides of (19). From (19), one can also derive the active power at the receiving end as a function of \( V_S \) and \( V_R \):
\[ P = 3[V_S V_R \cos(\theta_B - \delta) - A_L V_R^2 \cos(\theta_B - \theta_A)]/B_L \quad (20) \]
where \( \delta, \theta_A, \) and \( \theta_B \) represent the angles of \( V_S, A_L, \) and \( B_L \), respectively.
The theoretical maximum power occurs near 90 degrees when $\theta_B = 0$. In practice, however, the lines are never operated to deliver their theoretical maximum power. In order to maintain stability during transient disturbances, the maximum angular displacement across the line is on the order of 30 to 35 degrees [11]. In addition, the voltage drop limit $V_s/V_r \geq 0.95$ should not be violated. With these constraints, the maximum power transfer for long lines defined in (20) is limited to a value well below the line thermal limit $P_{\text{max}} = \sqrt{3} V_r I_c$, where $V_r$ is the nominal line voltage and $I_c$ is the current carrying capacity of the line.

### 3.2.2 Network Model at Harmonic Frequencies

At harmonic frequencies, the load is represented by a harmonic current source under the assumption that a portion of the load is nonlinear. The stiff generating source is represented by a short circuit since it generates only 60 Hz signals and its internal impedance is assumed to be zero. The resulting network circuit is shown in Figure 10 (b). In this case, the receiving end current is assumed to be known and the sending end voltage is zero.

The voltage-current relationships at each harmonic frequency of order $n$ are the same as (14) - (17) after evaluating the values of the series impedance and shunt admittance of the line at the $n$th harmonic frequency. Let the new quantities in (14) - (17) be identified with a subscript $n$. The sending end current and receiving end voltage are directly computed from (14) - (15):

$$V_{Rn} = -[B_{Ln}/A_{Ln}]I_{Rn} = Z_{Cn}\tanh(\gamma L)I_{Rn} \quad (21)$$
\[ I_{Sn} = [A_{Ln} - C_{Ln}B_{Ln}/A_{Ln}]I_{Rn} = \text{sech}(\gamma L)I_{Rn} \quad (22) \]

It is important to keep in mind, however, that signals at higher frequencies have shorter wavelengths. As a consequence, the magnitudes of the harmonic voltages and currents at some points on the line can be several times greater than those measured at the line terminals. The \( n \)th harmonic voltage and current at a point \( x \) miles away from the receiving end are expressed as a direct function of \( I_{Rn} \):

\[ V_{Xn} = [A_{Xn}Z_{Cn}\tanh(\gamma L) + B_{Xn}]I_{Rn} \quad (23) \]
\[ I_{Xn} = [C_{Xn}Z_{Cn}\tanh(\gamma L) + A_{Xn}]I_{Rn} \quad (24) \]

### 3.3 SERIES COMPENSATED NETWORK

#### 3.3.1 Network Model at Power Frequency

Figure 11(a) shows a series capacitor with reactance \( X_c \) placed \( X_i \) miles from the receiving end of the line. In order to determine the terminal voltage and current relations, the line may be considered as two line sections connected through the series compensator. Let section I represent the load side with sending end voltage \( V_A \) and current \( I_A \) (at right of capacitor terminal), and section II represent the generator side with receiving end voltage \( V_B \) and current \( I_B \) (at left of capacitor terminal). Replacing \( L \) by \( X_i \) and \((V_S, I_S)\) by \((V_A, I_A)\) in (14) - (15) yields the terminal voltage-current relationships for section I. Those of section II are obtained by substituting \( L \) with \( X_2 = L - X_i \). Let \((V_R, I_R)\) be replaced by \((V_B(X_i), I_B(X_i))\). With this notation, it should be obvious that \( I_A = I_B \), but the voltages differ due to the voltage drop across the capacitor:
Figure 11 - Series Compensated Line
(a) @Power Freq.  (b) @Harmonic Freq.
\[ V_B = -jX_CI_A + V_A \quad (25) \]

Substitution of (25) in the two sets of equations (14) - (15) yields the terminal voltage relationship of the entire line:

\[ V_S = K_1 V_R + K_2 S^*/3V_R \quad (26) \]

where,

\[ K_1 = A_{x2}A_{x1} + C_{x1}(B_{x2} - jX_C A_{x2}) \quad (27) \]

\[ K_2 = A_{x2}B_{x1} + A_{x1}(B_{x2} - jX_C A_{x2}) \quad (28) \]

The complex power can then be written in terms of the terminal voltages:

\[ S^* = [V_S V_R - K_1 V_R^2]/K_2 \quad (29) \]

from which the receiving end power is determined:

\[ P = 3[V_S V_R \cos(\delta - \theta_{k2}) - K_1 V_R^2 \cos(\theta_{k1} - \theta_{k2})]/K_2 \quad (30) \]

where \( \theta_{k1} \) and \( \theta_{k2} \) correspond to the angles of \( K_1 \) and \( K_2 \), respectively. Without the series capacitor, equations (29) and (30) reduce to (19) and (20), respectively.

### 3.3.2 Network Model at Harmonic Frequencies

At higher frequencies, the circuit shown in Figure 11(b) can be analyzed using the above procedure after adjusting the impedances at the appropriate frequency. Since the receiving end harmonic current is known and the sending end voltage is zero, the receiving end harmonic voltage is determined directly from (26):
The sending end current $I_{Sn}$ is found using (14), (15), and (25):

$$I_{Sn} = \left[ C_{X2n}A_{X1n} + C_{X1n}(A_{X2n} - jX_{Cn}C_{X2n}) \right] V_{Rn} + [C_{X2n}B_{X1n} + A_{X1n}(A_{X2n} - jX_{Cn}C_{X2n})] I_{Rn}$$

(32)

### 3.4 NUMERICAL EXAMPLE

To illustrate the effect of series capacitor placement on transmission line loadability and harmonic propagation, a 345 kV, 238 mile line located in the Southwest region of the United States is considered for line compensation. The line parameters are: series impedance $z = 0.435 + j0.603$ ohms/mile, shunt admittance $y = j6.876 \times 10^{-6}$ mhos/mile, current carrying capacity $I_c = 1050$ A, and fixed sending end line voltage $V_s = 345$ kV. The Surge Impedance Loading (SIL), a quantity often used as a base for line loadability, is computed to be $SIL = V_s/Z_c = 400$ MW (1.0 p.u.) and the thermal limit $P_{\text{max}} = 625$ MW (1.5 p.u.) without the compensator. The theoretical power transfer limit is nearly 790 MW (2.0 p.u.), but the practical line loadability is only 460 MW (1.15 p.u.) when considering voltage drop and phase angle limits imposed by stability constraints.

It is desired to use a series compensator to boost the line loadability up to the thermal limit. Figure 12 shows a three-dimensional plot of the line loadability (30) as a function of the capacitor size and location along the line. The compensator size is varied from 0 through 143 ohms, a value corresponding to 100% compensation. Unfortunately, the graph does not clearly indicate the minimum capacitor values that result in line
loadability near 1.5 \( p.u. \). Detailed analysis is obtained by plotting the power transfer in two-dimensional graphs where one of the two variables is kept constant.

Figure 13 shows the maximum power transfer as a function of capacitor size at four different line locations: receiving end, 1/3 of line length, 2/3 of line length, and sending end. The horizontal line in the Figure represents the thermal limit \( P_{\text{MAX}} \). The graphs indicate that the minimum capacitive reactance that can boost the line loadability to its thermal limit is near 40 ohms. Figure 14 reveals more detail on the variation of the line loadability as a function of compensator location for 3 capacitive reactances near the value above \( X_c = 40, 41, 42, \& 43 \) ohms. The horizontal line in figures 13 and 14 represents the thermal limit \( P_{\text{MAX}} \).

Note that a 40 ohm reactance increases the power transfer capability up to or above \( P_{\text{MAX}} \) only if it is placed between 70 and 140 miles away from the receiving end. A 42 ohm reactance also fails to increase the power transfer to the thermal limit if placed within 5 miles of the sending end. The minimum capacitive reactance that increases the line power transfer to the thermal value when placed anywhere along the line is 43 ohms. The corresponding MVAR capacitor size for a current rating equal to the current carrying capacity is 47.5 MVAR/phase.

At harmonic frequencies, the receiving end current is set equal to 1 Amp at each of the characteristic harmonic frequencies up to the 25th harmonic. It is desired to determine the propagation of these harmonic currents along the line, current injected into the generator unit \( I_{sn} \), harmonic voltage at the load bus \( V_{rel} \), and the effect of the series compensator on these quantities. Figures 15 and 16 show the negative sequence \( (n = 5, \cdot \cdot \cdot) \).
Fig. 13 - Max. Power vs Capacitor value

capacitor distance from receiving end

Maximum Power Transfer (MW)

Capacitive Reactance (Ohms)

0 mi.  79 mi.  158 mi.  238 mi.

3,000  2,500  2,000  1,500  1,000  500

Thermal Limit (Pmax)
Fig. 14 - Max Power vs Capacitor Location

(effect of capacitive reactance)
Figure 15 - Negative Sequence Currents
(Harmonics without series compensator)

Harmonic Current (A)

Distance From Receiving End (miles)
Figure 16 - Negative Sequence Voltages
(Harmonics without series compensator)
11, 17, & 23) harmonic current and voltage standing wave patterns along the line without the series compensator. Note that the signals do not become amplified significantly except for the 23rd harmonic that resulted in a sending end current 6.5 times larger than that at the receiving end. The resulting receiving end harmonic voltage is nearly 2 kV, a value above the 1% recommended limit [5]. In practice this magnitude will be damped by the larger line resistance at 1380 Hz and the nonzero source impedance, but nonetheless it must not be ignored. Figures 17 and 18 show that the positive sequence harmonic currents and voltages are not significantly amplified.

In order to determine the voltage and current magnitudes at other harmonic frequencies, a frequency scan of the sending end current and receiving end voltage was performed from 0 Hz to 1500 Hz and the results are shown in figures 19 and 20. Such curves are expected since they represent the magnitudes of the hyperbolic functions described in (21) and (22). Note that for higher frequencies the characteristic impedance \( Z_{en} \) is constant, while the propagation constant is proportional to frequency. The marks on the curves correspond to the characteristic harmonic frequencies. The relatively large amplification of the 23rd harmonic (1380 Hz) is evident.

The curves in figures 19 and 20 include the case where a 43 ohm capacitive reactance is installed on the line. Note that the curves differ only at low frequencies, and overlap at higher frequencies. This is due to the fact that the series capacitor behaves like a short circuit at high frequencies; hence, it will have little or no effect on the high frequency characteristics of the line. At sub-harmonic frequencies, however, the series compensator has a dramatic effect.
Figure 17 - Positive Sequence Currents
(Harmonics without series compensator)

- 7th
- 13th
- 19th
- 25th
Figure 18 - Positive Sequence Voltages (Harmonics without series compensator)
Figure 19-Sending End Current vs Freq.
(@Characteristic Harmonic Frequencies)
Fig. 20- Receiving End Voltage vs Freq.
(Characteristic Harmonic Frequencies)

Receiving End Voltage (V)

Frequency (Hz)

- Without Capacitor
- With Capacitor

5, 7, 11, 13, 17, 19, 23, 25
CONCLUSIONS

This research emphasized the complications encountered when designing compensators for power factor correction and harmonic reduction in industrial power systems where compensation is desired at more than one bus. The presence of multiple capacitors causes additional resonant frequencies that must be avoided throughout the operating power factor range. An analytical formulation for a quick calculation of the resonance conditions has been presented for a typical industrial power system configuration.

This work also investigated the series capacitor placement problem on long transmission lines and possible resonance effects at harmonic frequencies. The study showed that some capacitor sizes allow the line to reach or exceed its thermal limit only when placed within a specific section of the line. The minimum capacitor size that allows maximum power transfer, when placed anywhere on the line, was determined. With regard to the harmonics, it was found that series capacitors have a noticeable effect on the frequency response of the network at very low frequencies (sub-harmonics), but little or no effect at higher frequencies. It is important to note that the harmonic response is predominantly a function of the transmission line parameters. As such, it is theoretically possible that severe harmonic effects can occur given certain line parameters.

Harmonics should be considered when designing all aspects, not just those contained herein, of power systems. A great deal of research still needs to be done in this
area to provide the designer with additional insight into methods of maximizing power system capability, while minimizing the unwanted harmonic effects.
BIBLIOGRAPHY


