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A Detailed Circuit Analysis of the Lawrence Livermore National Laboratory Building 141 Detonator Test Facility

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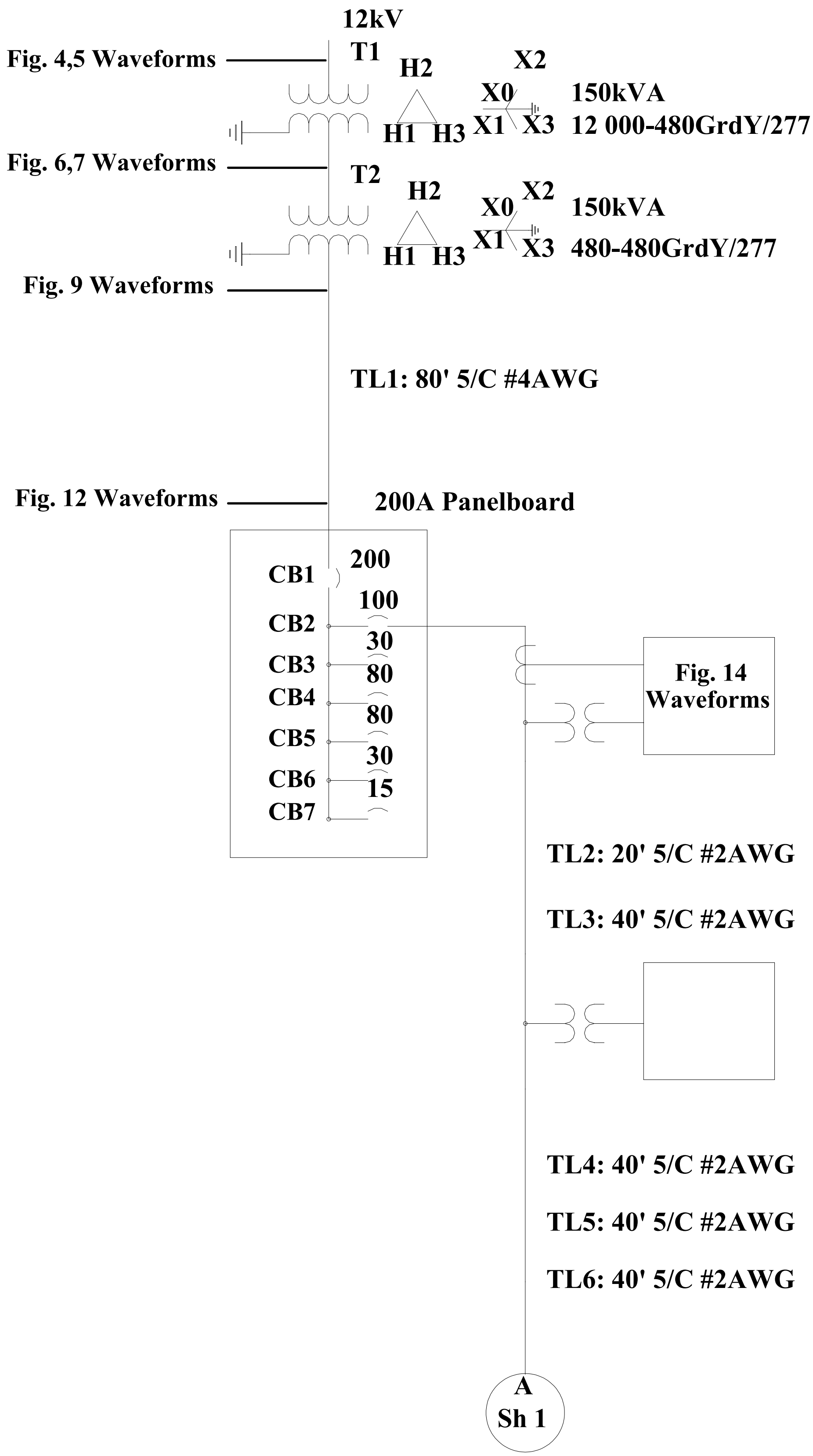
Abstract

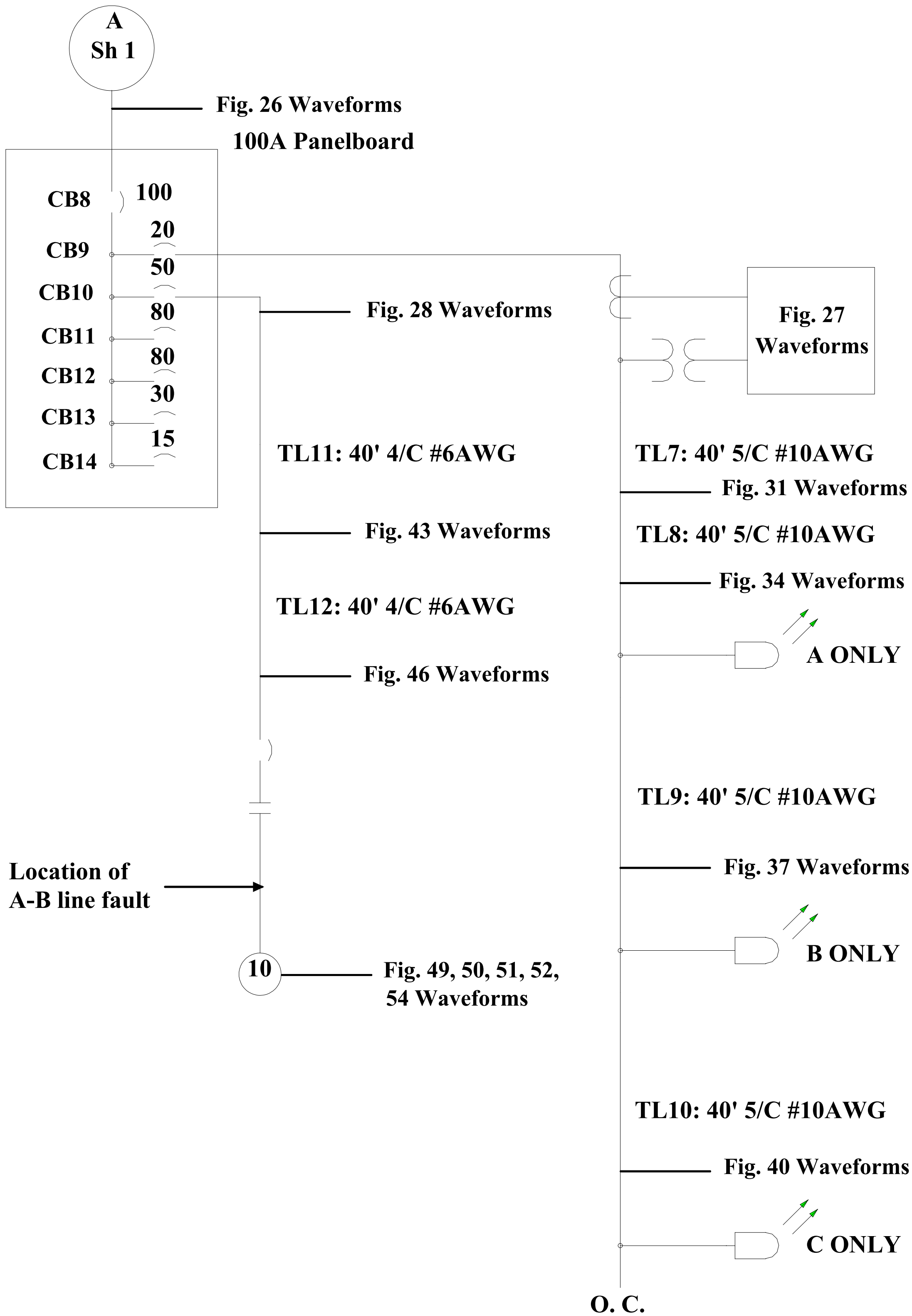
A detailed electrical equivalent circuit of an as-built utility fault simulator is presented. Standard construction techniques for light industrial facilities were used to build a test-bed for evaluating utility power level faults into unintentional victims. The initial components or victims of interest are commercial detonators. Other possible candidates for fault response analyses include motors, power supplies, control systems, computers, or other electronic equipment. Measured Thevenin parameters of all interconnections provide the selected component values used in the model. Included in the model is an opening 10 HP motor circuit demonstrating voltage transients commonly seen on branch circuits from inductive loads common to industrial installations. Complex transmission lines were developed to represent real world transmission line effects possible from the associated branch circuits. To reduce the initial circuit stabilization delay a set of non-linear resistive elements are employed. The resulting model has assisted in confirming previous detonator safety work and supported the definition of critical parameters needed for continued safety assessment of victims to utility type power sources.

Introduction

We have developed a MicroCap 7.0 [1] electric circuit model for the Lawrence Livermore National Laboratory (LLNL) Building 141 (B141) Detonator Test Facility [2]. This model consists of a three-phase voltage source; a linear three-phase, 150 kVA, 12 kV-to-480 V, delta-wye transformer; a linear, three-phase, 150 kVA, 480 V-to-480 V, delta-wye transformer; a three-phase, 200 A distribution panel; a three-phase, 100 A distribution panel with a five-wire input, a five-wire output, and a four-wire output; three sets of fluorescent lamps represented by one-Ohm resistors; a three-phase bank of 10 GOhm lamp circuit termination resistors, representing an open circuit; a 10-horsepower(hp), three-phase motor at steady state, represented by current sources, inductors, resistors, and voltage sources; and twelve three-phase transmission lines of lengths from 20 to 80 feet. The two transformer models represent generic transformers with representative component values. The 10-hp motor model is also generic; its behavior is nominal for its power rating. The three-phase, 10-hp motor serves as the load for the distribution circuit. The motor is initially connected to the circuit at the start of the simulation. The motor is located at the termination of the branch circuit, which connects to the lower set of output terminals for the 100 A distribution panel. A one-line diagram of the electric model is shown in Fig. 1. Each transmission line model is denoted as "TL*i*," where *i* varies from 1 to 12. The first transmission line model is TL1, and the last transmission line model is TL12. Each circuit breaker in the distribution panels is denoted by "CB*i*," where *i* now varies from 1 to 14. The locations of the points, where the various waveforms are calculated, are indicated on Fig 1.



(a) First sheet of the one-line diagram



(b) Second sheet of the one-line diagram

Figure 1. One-line Diagram of the Electric Circuit Model

We describe the electric circuit model in some detail. Since the electric circuit model for the test facility is fairly large and complicated, it is presented in the figures as a number of small electric circuits. These circuits have labeled terminals at the relevant input and output points. If all the terminals with the same labels on the various figures are connected together, the total electric circuit will be assembled. A block diagram of the interconnection of these electric circuit schematics is shown in Fig. 2. The figures, which describe each circuit component, are shown at the bottom of each component block. We also present a number of voltage and current waveforms produced by the model.

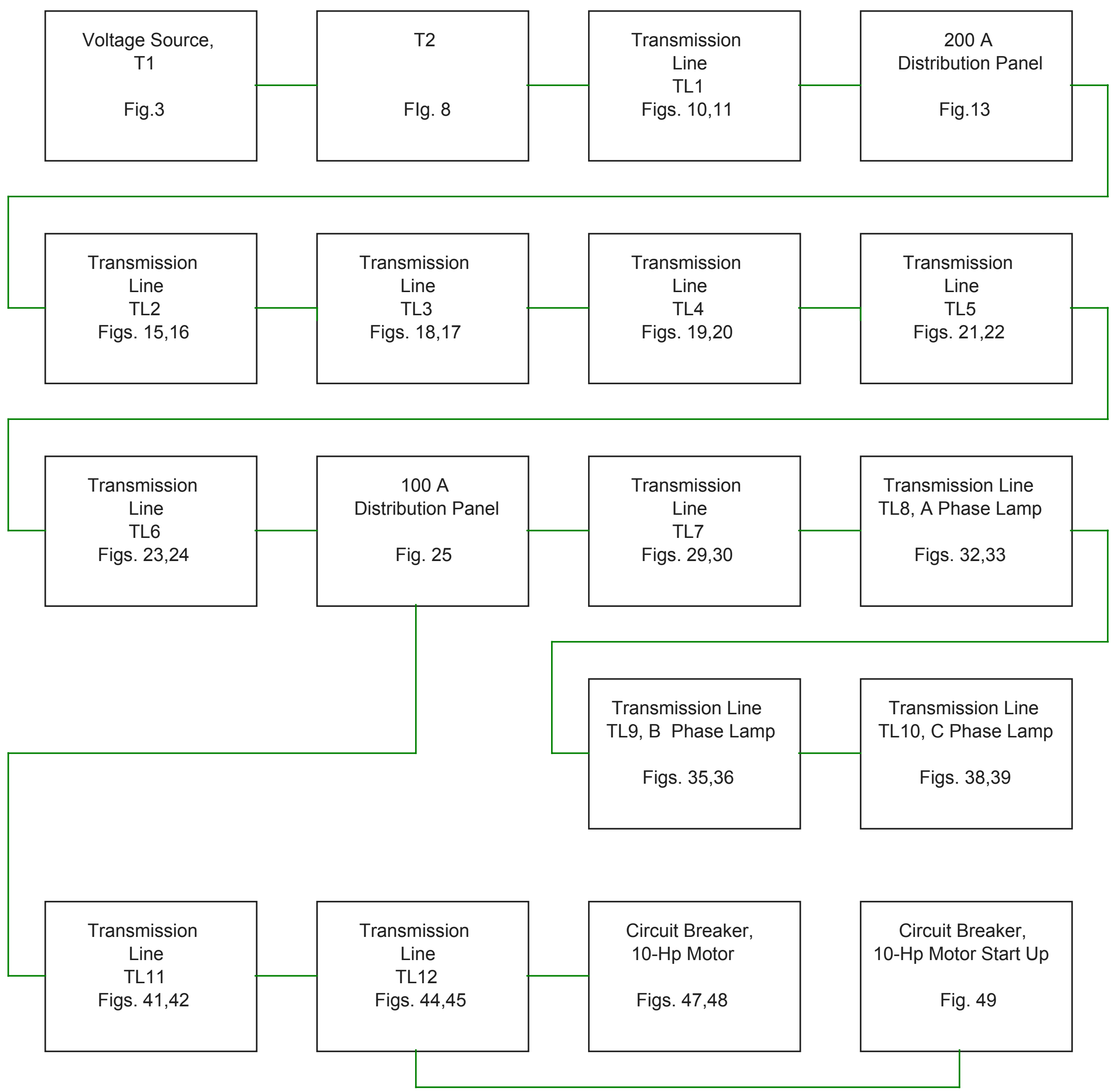


Figure 2. Block Diagram of the Electric Circuit Schematics

The Three-Phase Voltage Source Model

The three-phase voltage source model consists of three 60 Hz, 9798 V, sine-wave voltage sources – V1, V2, and V3; three series, 2.3 mOhm resistors – R1, R2, and R3; three series 1.2 mH inductors – L1, L2, and L3; two series time-variable switch resistors, R661 and R662, which function as time-delayed closing switches to connect two of the voltage source phase voltages to the 12 kV-to-480 V transformer model. The electric circuit schematic for this three-phase voltage source model is shown in Fig. 3, which also includes the T1 transformer model connected to the right side of the three-phase source model. The voltage source V1 starts at the simulation time, t = 0, with zero phase angle. The voltage source V2 starts at the same time with a phase angle of –120 degrees. The voltage source V3 starts at the same time with a phase angle of –240 degrees. The voltage generated by the voltage source, V1, is shown out to 30 msec in the top frame of Fig. 4 by the curve labeled as "V(20)." This is the voltage between schematic node 20 and ground. The voltages generated by the voltage sources, V2 and V3, are shown on the top frame of Fig. 4 by the curves labeled V(24) and V(22), respectively. The line supplied by V1 is chosen as the A phase line, the line supplied by V2 is chosen as the B phase line, and the line supplied by V3 is chosen as the C phase line. R1 is connected to the positive terminal of V1, R3 is connected to the positive terminal of V2, and R2 is connected to the positive terminal of V3. The series inductors, L1, L2, and L3, are connected to R1, R3, and R2, respectively. The switch resistor R661 has a value of 1 GOhms until about 5.53 msec into the simulation when it smoothly transitions to 1 mOhm, allowing the A phase voltage to be applied to the T1H1 high-voltage terminal of the first 150-kVA transformer model. The time dependence of the R661 resistance is given by the expression indicated by the functional component description, (x), in Fig. 3. In the expression, "T" denotes time, "M" denotes 0.001, and "U" denotes 1.e-6. Similarly, the switch resistor R662 makes the same resistance transition at about 9.66 msec, connecting the B phase voltage to the T1H2 high-voltage terminal of the first 150-kVA transformer model. The time dependence of the resistance of R662 is given by the expression indicated by the functional component description, (y), in Fig. 3. The C phase voltage is applied immediately at the T1H3 high-voltage terminal of this transformer model, T1.

The 150-kVA, 12 kV-to-480 V, Delta-Wye Transformer Model

The 150-kVA, three-phase, 12 kV-to-480 V, delta-wye transformer model is for the first transformer, T1, to the right of the three-phase voltage source. The schematic of this model is shown in Fig. 3. This model consists of three linear, single-phase transformer models – K16, K17, and K18 – with the high-voltage sides connected in a delta configuration, and the low-voltage sides connected in a wye configuration with the neutral terminal T1X0 connected to each of the positive polarity secondary outputs. The low-voltage phase terminals, T1X1, T1X2, and T1X3, are connected to the secondary negative polarity outputs for the input phases, C, A, and B, respectively. K16 has a primary inductance of 23.1715823 H, a secondary inductance of 12.346752 mH, and a coupling coefficient of 0.999060384. The extreme number of significant digits used for these three numbers are required for proper operation of K16 in the circuit simulation. K17 and K18 have the same values for these defining parameters. Each primary phase circuit of T1 has resistance of 80 mOhms, divided equally between input and output (positive and negative terminal) resistor pairs. These pairs of resistors are R494 and R500, R495 and R501, and R496 and R502. Each secondary circuit of the transformer model has a series resistance of 0.4 mOhms. These secondary series resistances are divided equally between the input and output resistor pairs – R497 and R503, R498 and R504, and R499 and R505. Resistors of 1 mOhm are placed in the secondary phase lines from the T1 low-voltage terminals – T1X1, T1X2, T1X3, and T1X0. These resistors are respectively labeled R690, R691, R692, and R693, as shown in Fig. 8.

The initial 30 msec of simulated voltages at the T1 high-side phase terminals with respect to the ground terminal are shown in the bottom frame of Fig. 4. V(T1H1) is the voltage at the T1H1 terminal. Likewise, V(T1H2) and V(T1H3) are the voltages at the other two terminals, T1H2 and T1H3, respectively. It can be seen that the voltage at T1H1 turns on at about 5.53 msec into the simulation. This turn on induces a voltage transient at terminal T1H2. The true voltage at T1H2 turns on at about 9.66 msec into the simulation. After about 9.66 msec, the high-side T1 phase-to-ground voltages track the corresponding source voltages in time and have amplitudes slightly lower due to the voltage drops across resistors, R1, R3, and R2, and the inductors, L1, L2, and L3. The T1 primary phase currents are shown in Fig. 5 on the bottom frame. The current into the T1H1 terminal is labeled "I(L1)," since it is also the current flowing through the inductance, L1. The current into the T1H2 terminal is labeled "I(L2)," and the current flowing into the T1H3 terminal is similarly labeled "I(L3)." No current flows until after about 5.53 msec, when a circuit is completed by the closure of the switch resistor, R661. Current then begins flowing through terminals T1H1 and T1H3 and builds up in absolute value as time passes. At about 9.66 msec, the switch resistor, R662, closes and induces low-amplitude, high-frequency transient currents in all three-phase lines. These transients die out over about 7 msec, and the three primary T1 phase currents approach a steady state AC (alternating current) condition. The two programmed, nonlinear resistors are used as switches in order to implement a smoother, less abrupt switching than is possible with the timed switch models, which are available in the MicroCap component library. Smaller amplitude switching transients are thus generated at the switching times of 5.53 and 9.66 msec.

The voltages at the T1 secondary terminals are shown in Fig. 6 on the bottom frame out to 30 msec into the simulation. At about 5.53 msec, after the first switching event in the primary circuits occurs, voltages appear at the T1X1 and T1X3 terminals. At about 9.66 msec, a nonzero voltage appears at the T1X2 terminal. This voltage is accompanied by high-frequency transients on all three secondary voltage waveforms. After a short time of approximately 8 msec, these transients die off and the phase voltages reach an AC steady state. The currents through the T1 secondary terminals are shown in bottom frame of Fig. 7 out to 60 msec. The current through the T1X1 terminal is labeled as "I(R690)," since it is also the current through R690. Figure 8 shows the locations of the resistors, R690, R691, and R692. The current through the T1X2 terminal is labeled "I(R691)," since it is also the current through R691. The current through the T1X3 terminal is labeled "I(R692)," since it is also the current through R692.

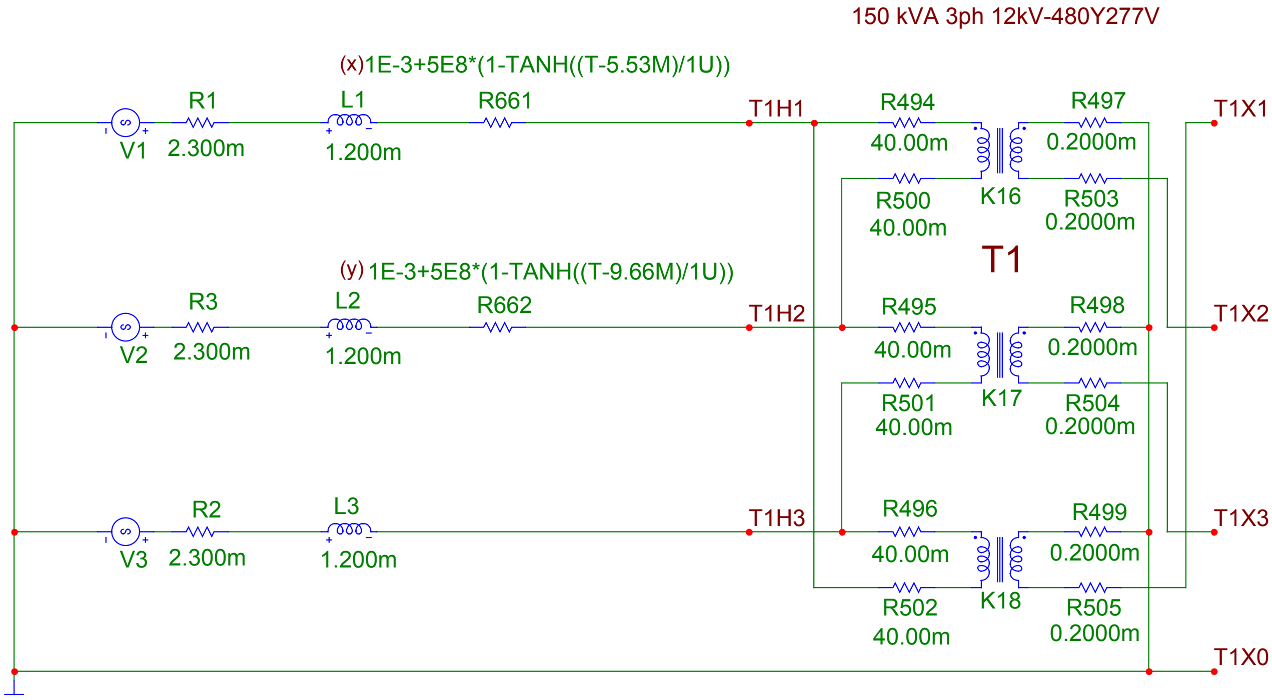


Figure 3. Electric Circuit Schematic of the Three-Phase Voltage Source and Transformer Model T1

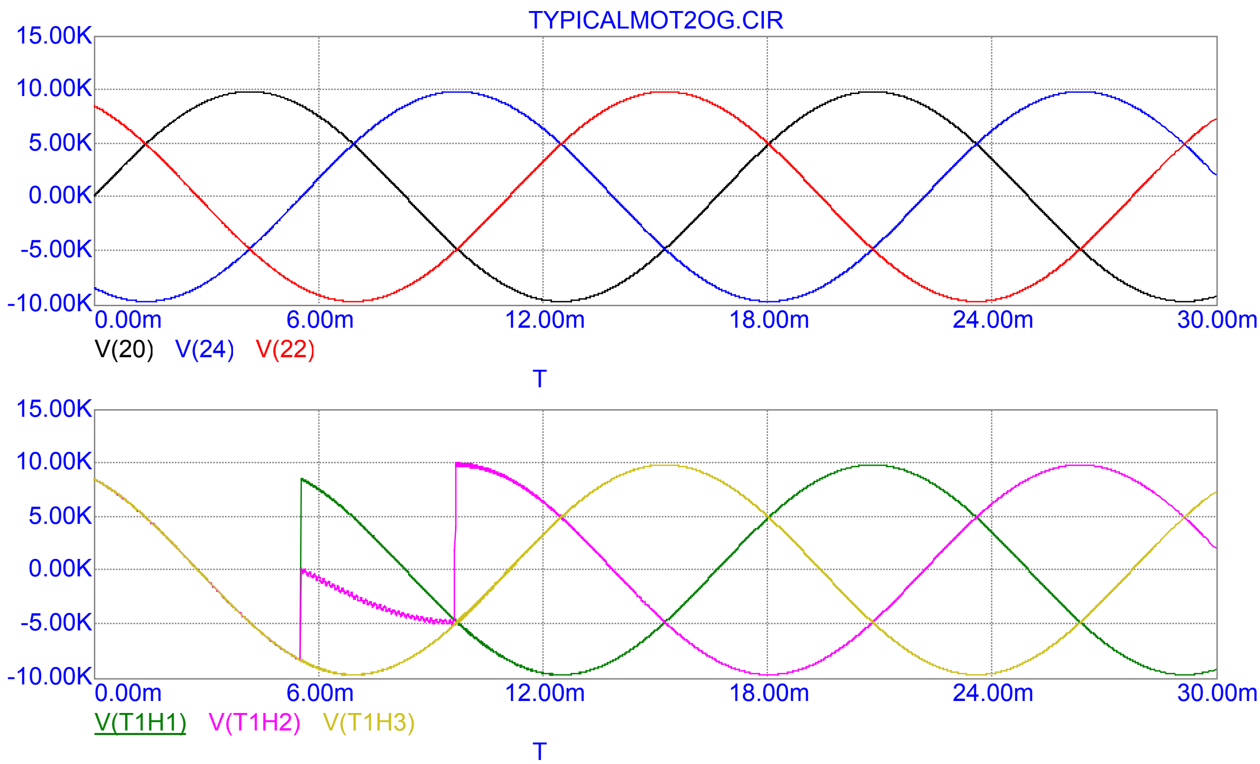


Figure 4. Source Voltages and T1 Input Voltages Referred to Ground

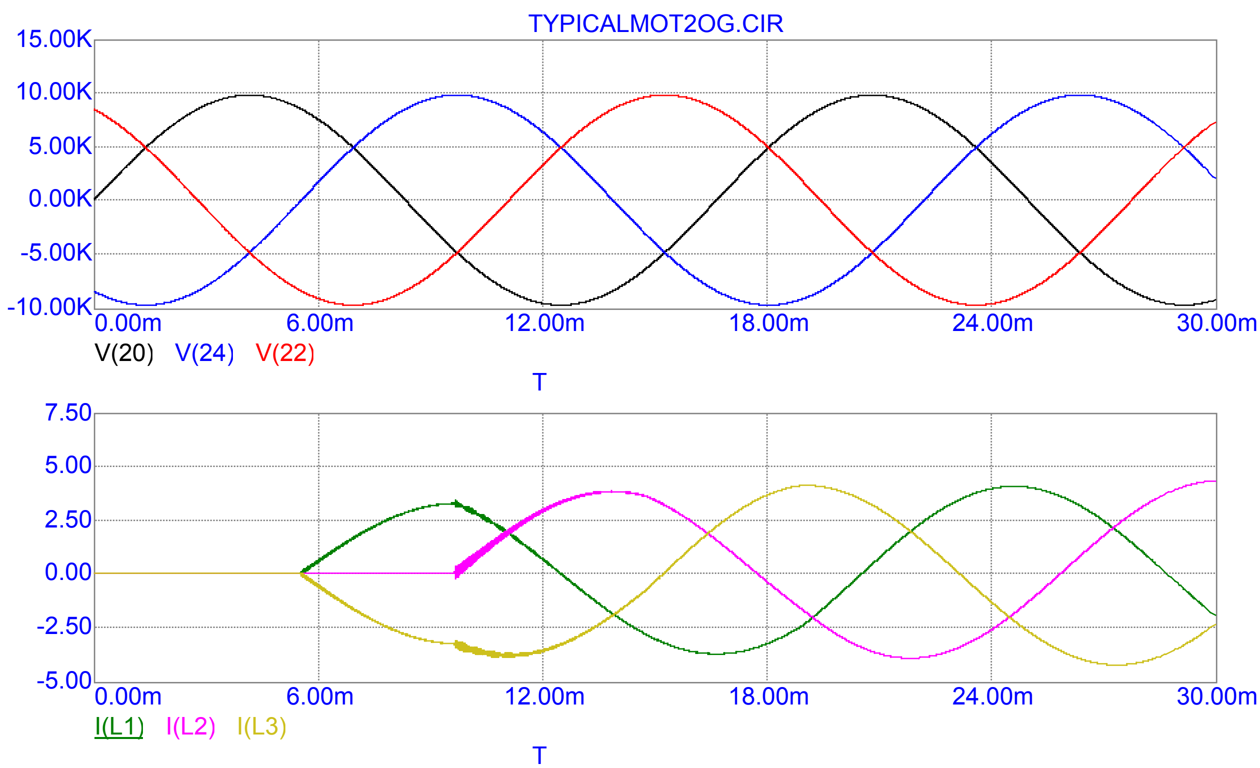


Figure 5. Source Voltages and T1 Primary Currents

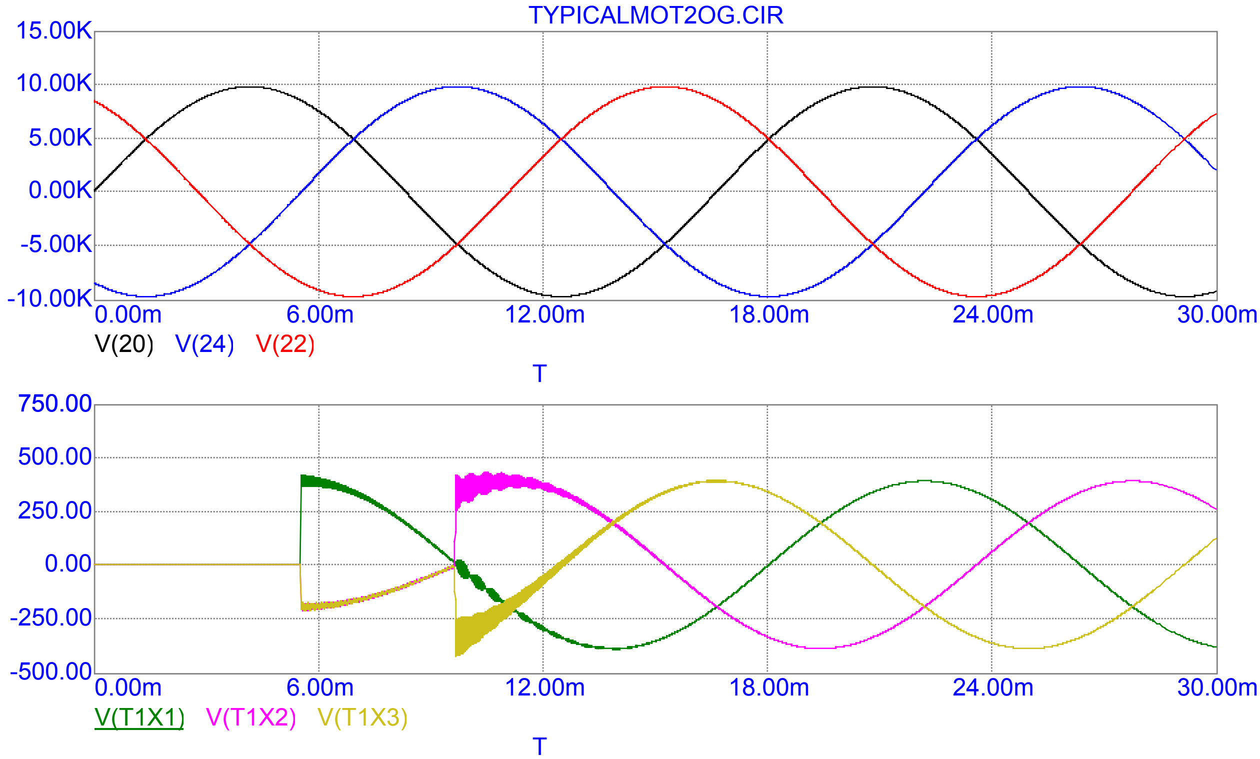


Figure 6. Source Voltages and T1 Secondary Voltages

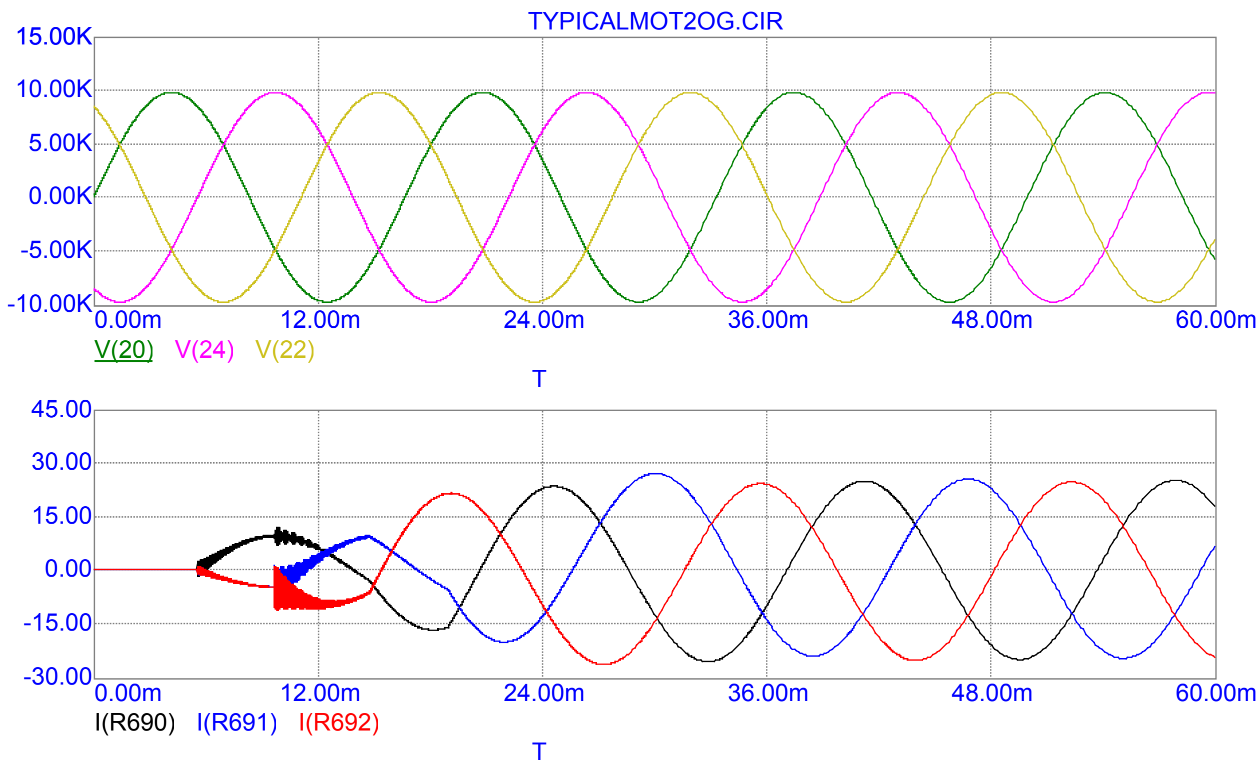


Figure 7. Source Voltages and T1 Secondary Currents

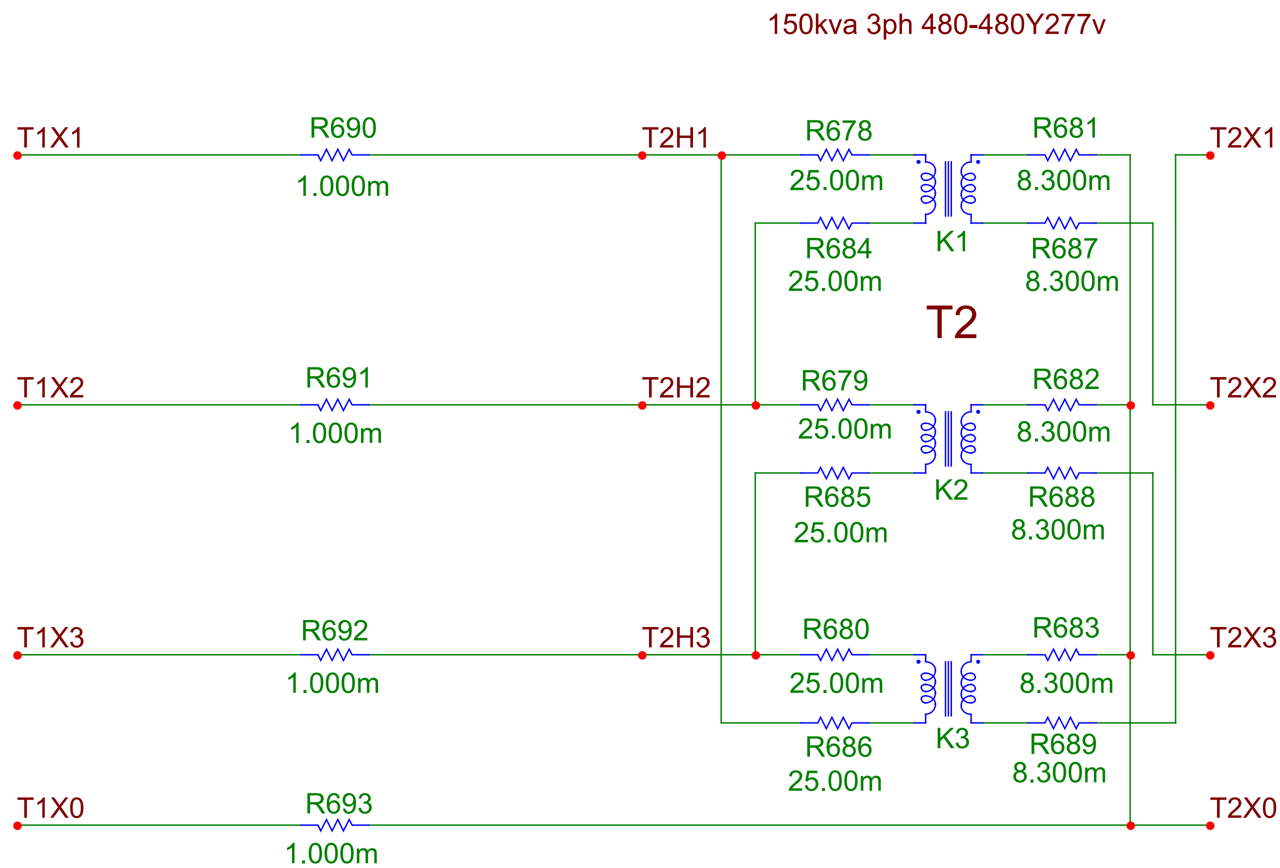


Figure 8. Electric Circuit Schematic of the Transformer T2 Model in the Circuit

The 150-kVA, 480 V-to-480 V, Delta-Wye Transformer Model

The 150-kVA, three-phase, 480 V-to-480 V, delta-wye transformer model, T2, is shown in Fig. 8. It follows the four resistors, R690, R691, R692 and R693. It also consists of three linear transformer models. These models are labeled K1, K2, and K3. The primary sides, towards transformer model T1, are connected in the delta configuration; the secondary sides are connected in the wye configuration. The primary terminals of T2 are labeled “T2H1,” “T2H2,” and “T2H3.” On the secondary side of T2, the neutral terminal is T2X0. It is connected to each of the positive polarity secondary outputs. The negative polarity secondary output terminals of T2 serve as the phase output terminals, designated “T2X1,” “T2X2,” and “T2X3.” The transformer model K1 has a primary inductance of 0.330506833 H, a secondary inductance of 0.110016213 H, and a coupling coefficient of 0.99976883. The extreme number of significant digits in these three numbers is required for proper operation of the model in the circuit simulation. The transformer models K2 and K3 have the same defining values as K1. Each primary circuit of T2 has a series resistance of 50 mOhm, split equally between the input and return line resistor pairs – R678 and R684, R679 and R685, and R680 and R686. Each secondary circuit of T2 has a series resistance of 16.6 mOhm, equally divided between the input and return resistor pairs. These pairs are R681 and R687, R682 and R688, and R683 and R689.

The voltages at the left terminals of T2 are essentially those shown in Fig. 4 since the voltage drops across the resistors, R690, R691, and R692, are small compared to the output voltages from T1. The voltages at the input terminals of T2 are typically about 20 mV less than those at the output terminals of T1 at the cycle peaks for normal operation. The currents into the terminals T2H1, T2H2, and T2H3 are the currents shown in Fig. 7.

The T2-output terminals are followed by TL1, which is shown in Figs.10 and 11.The voltages at the T2 output terminals are shown in Fig. 9 in the top frame out to 130 msec into the simulation. The currents through these output terminals are shown in the same figure in the bottom frame. The current through the T2X1 terminal is labeled

"I(R689);" the current through the T2X2 terminal is labeled "I(R687);" and the current through the T2X3 terminal is labeled "I(R688)." The transients beginning at 100 msec are due to a simulated line-to-line short circuit with switch resistor R1000 and the disconnection of the 10-hp motor model by the motor circuit breaker switch resistors, RCB1A, RCB1B, and RCB1C. These switch resistors are shown in Fig. 47. The positive and negative pulses in the currents at about 100 msec are due to the short circuit. After the transients have died out, the output voltages achieve a steady AC state, and the output currents drop to effectively zero.

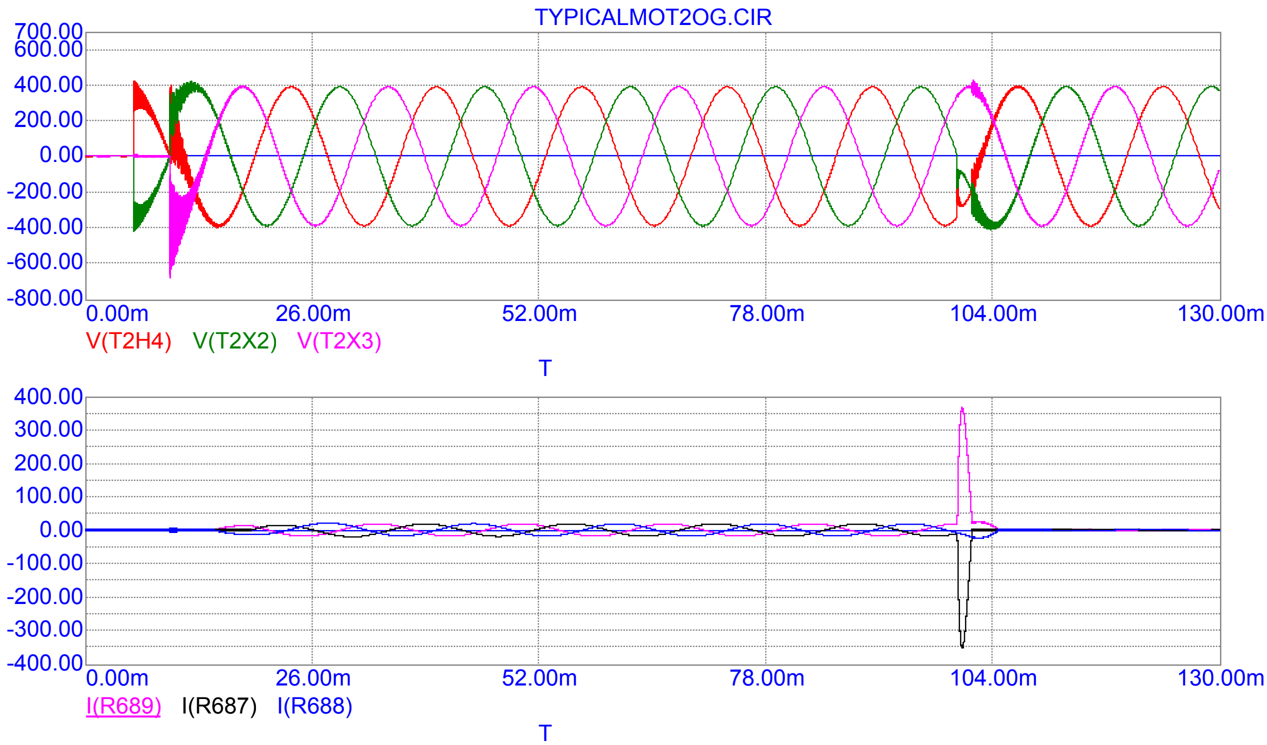


Figure 9. T2 Secondary Voltages and Currents

The Three-Phase Transmission Line Models

The twelve three-phase transmission line models represent transmission lines with the lengths of 80, 20, 40, 40, 40, 40, 40, 40, 40, 40, 80 and 80 feet. Each transmission line model consists of four series RLC sections with the shunt capacitances of each section to the left and followed by the series inductances and series resistances. The electric circuit schematic for TL1 is shown in Figs. 10 and 11. Figure 10 shows the first two sections, and Figure 11 shows the last two sections. TL1, representing an 80-foot physical transmission line, consists of five parallel lines – three phase lines, a neutral line, and a ground line. The phase lines represent three No. 4/0 American Wire Gauge (AWG) insulated wires in the bottom of a 3-inch-diameter Electrical Metallic Tubing {EMT) conduit. The neutral line represents one No. 4/0 AWG insulated wire. The ground line represents one bare conductor of No. 4/0 AWG. Mutual inductances between the lines and any effects of the conduit are ignored in the model. The top line of TL1 is taken to be the A phase line, which is labeled "20FTL_AIn2" at the left or input terminal set of the model. The next line down is taken to be the B phase line, which is labeled "20FTL_BIn2" at the input side. The third line down is taken to be the C phase line and is given the label "20FTL_CIn2" at the input. The fourth line down is taken to be the neutral line. It is designated "20FTL_NIn2" at the input. The fifth line down is the ground line. It is labeled "20FTL_GIn2" at the input point. It is connected to a circuit ground symbol at the input. In each T-section of the model, ten shunt capacitances are connected between the five lines. The capacitance values are one-fourth of the values derived from experimental measurements by Michael J. Wilson [3]. The value of each capacitance is generally different. Each line in each T-section has a series inductance and a series resistance. Once again, each value is one-fourth of the value derived from measurements by Michael J. Wilson. [3] Ten capacitances, five inductances, and five resistances constitute the full number of circuit components for each T-section for a five-wire transmission line model. The phase voltages at the input to TL1 are shown in the top frame of Fig. 9, and the corresponding input current waveforms are shown in the bottom frame. The phase voltages to ground at the output from TL1 are shown in the top frame of Fig. 12. The voltage at point B1 in Fig. 11 is labeled "V(82)," the voltage at point B2 is labeled "V(85)," and the voltage at point B3 is labeled "V(88)." The corresponding phase currents at the output from the first transmission line are shown the bottom frame of Fig. 12. The current in the top line, the A phase, is labeled "I(R727)." The current in the second line down from the top, the B phase, is labeled "I(R728)." The current in the second line down from the top, the C phase, is labeled "I(R729)."

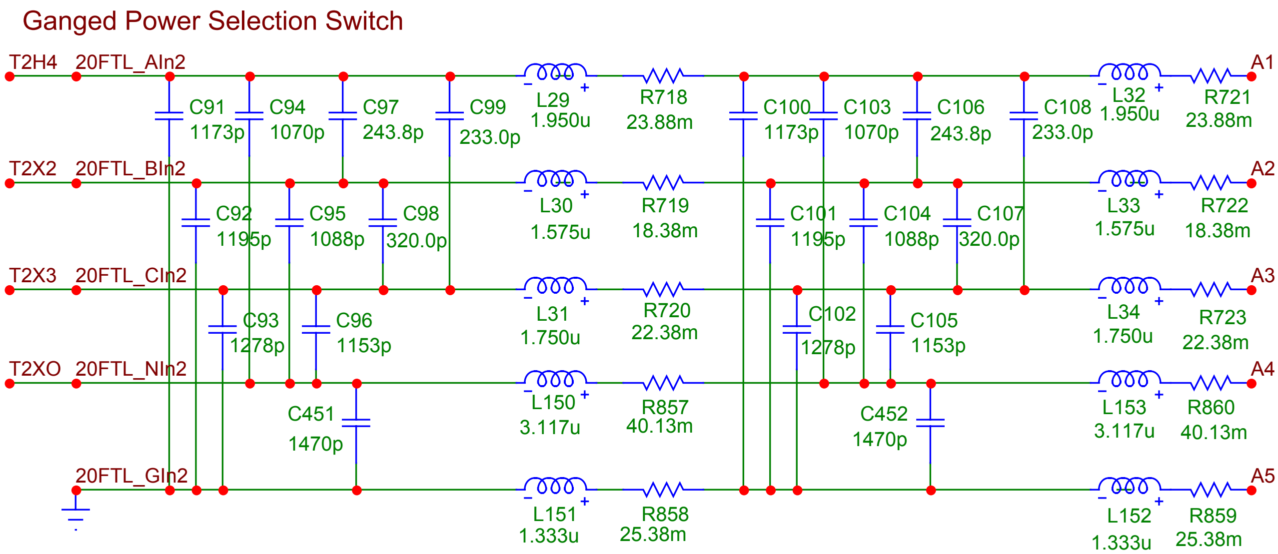


Figure 10. Electric Circuit Schematic of the First Two Sections of TL1

The connections to the transformer T2 output terminals are shown at the left. The connections to the last two sections of TL1 are shown at the right.

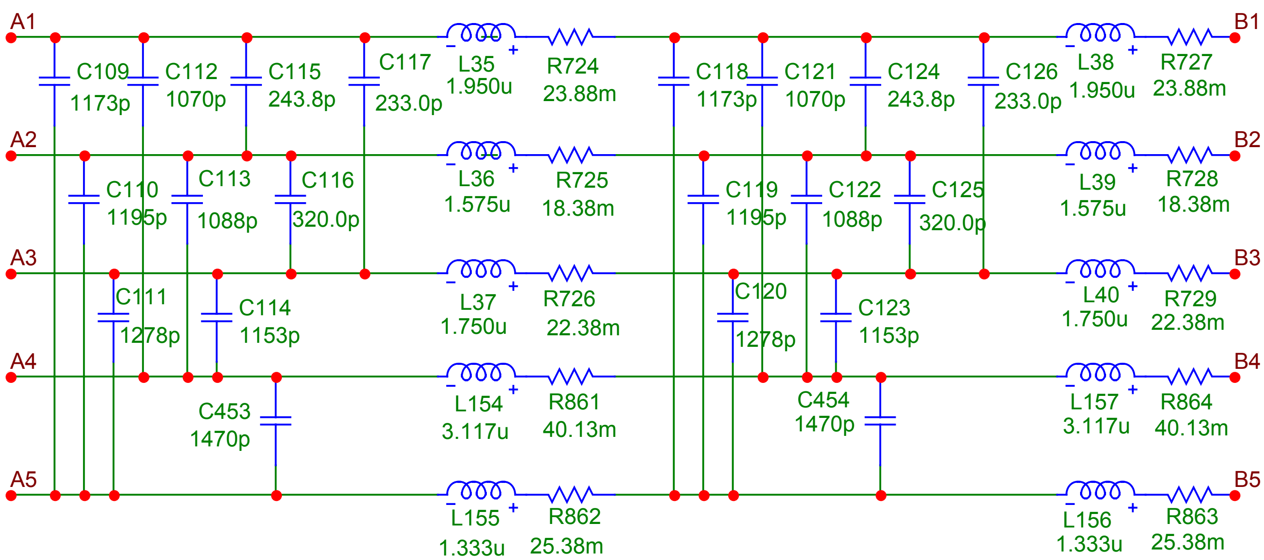


Figure 11. Electric Circuit Schematic of the Last Two Sections of TL1

The connections to the first two sections of TL1 are shown at the left. The connections to the rest of the circuit are shown at the right.

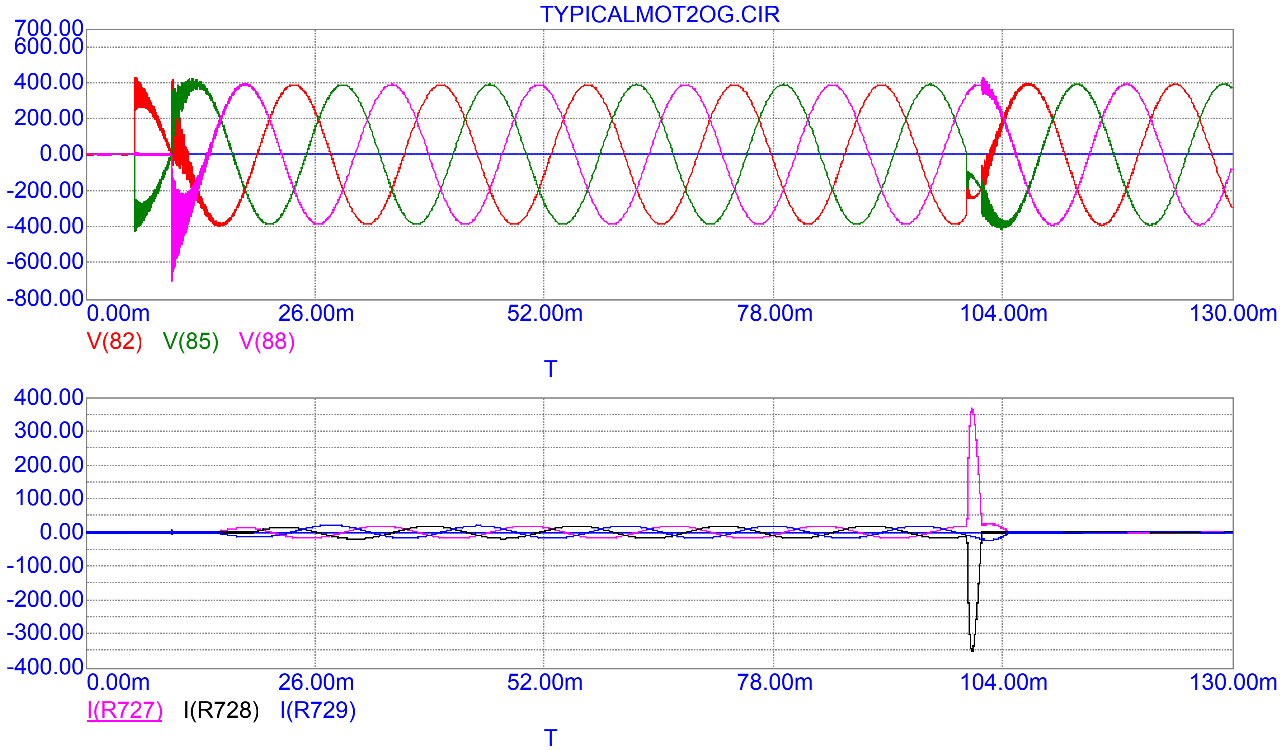


Figure 12. Phase Voltages and Currents at the Input to CB1

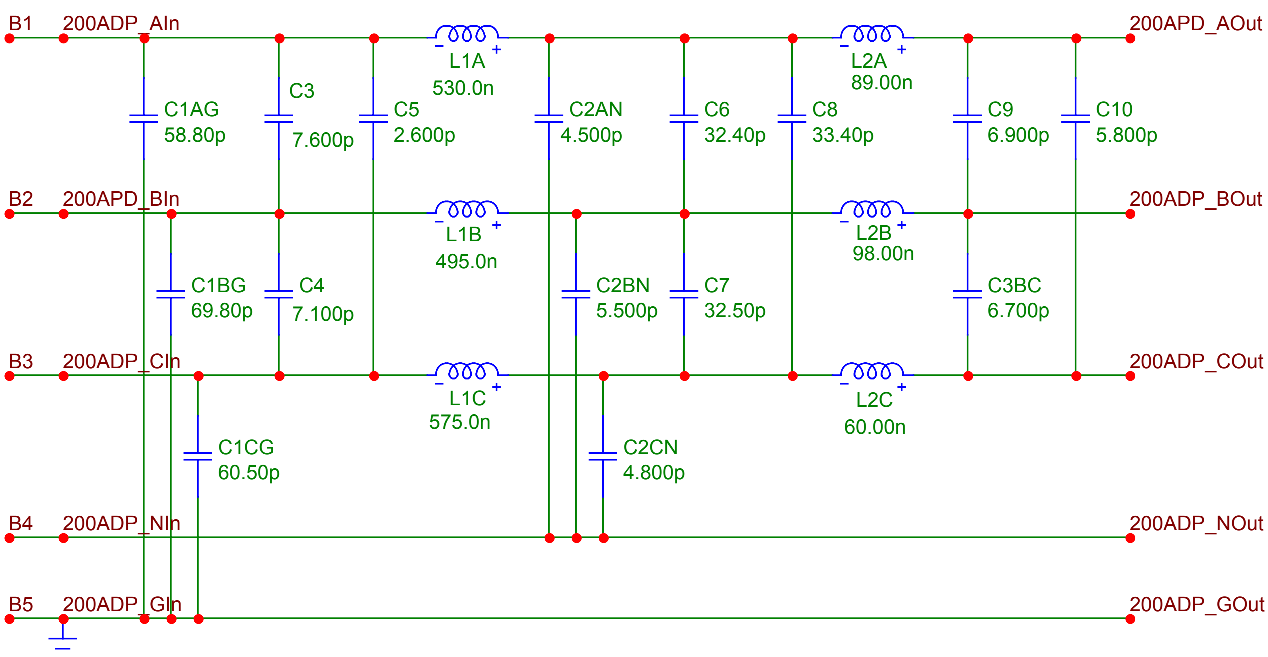


Figure 13. Electric Circuit Schematic of the 200 A Distribution Panel Model

The output of TL1 connects to the input side of the 200 A distribution panel model This model is shown in Fig. 13. The five input terminals of this distribution panel model are labeled “200ADP_AIn” for the A phase input, “200ADP_BIn” for the B phase input, “200ADP_CIn” for the C phase input, “200ADP_NIn” for the neutral input, and “200ADP_GIn” for the ground input. These five input terminals can be more briefly referred to as “200ADP_XIn,” where X = A, B, C, N, or G. The phase voltages and currents at the input to this distribution panel model are shown in Fig. 12. The transients at about 112 msec are due to the opening of the motor circuit breaker switch resistors, RCB1A, RBC1B, and RBC1C, as they transition to resistance values of 1 GOhm and remove the motor from the branch circuit. The output phase voltages and currents from the 200 A distribution panel model are shown in Fig. 14. This model is further described in a subsequent section, entitled “The 200 A Distribution Panel Model.”

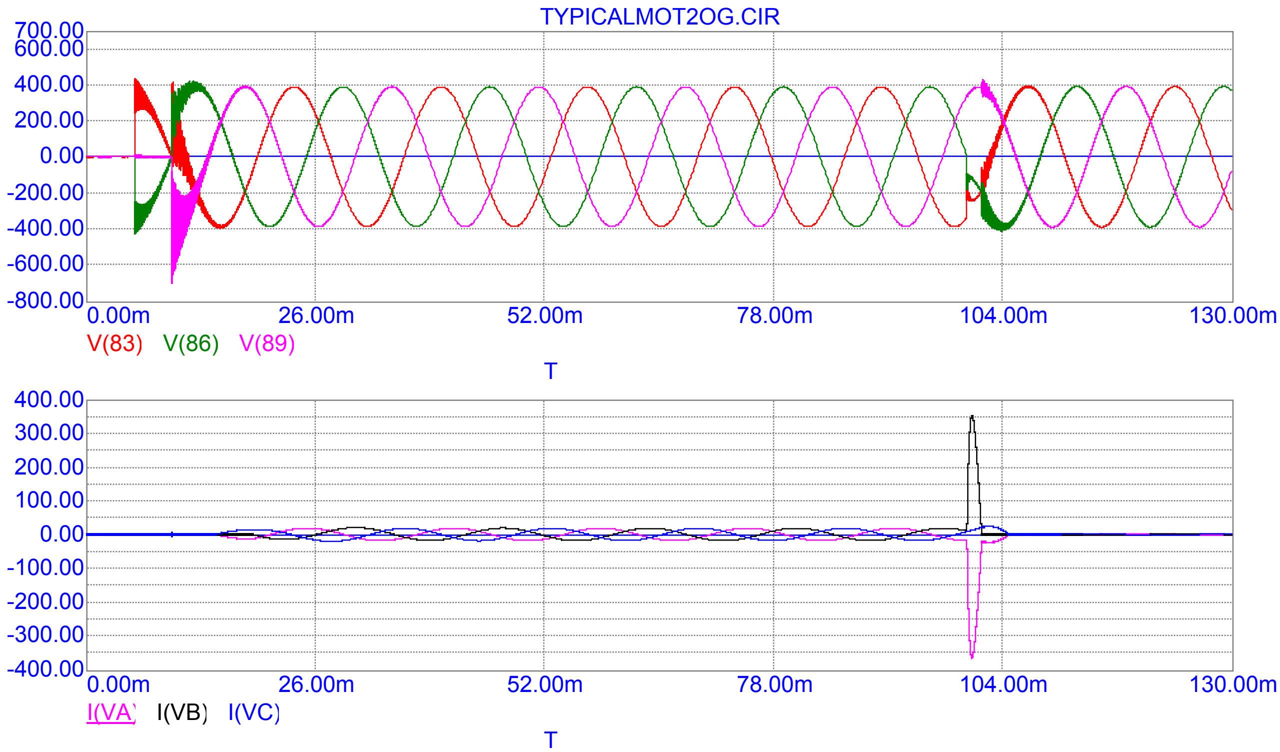


Figure 14. Phase Voltages and Currents at the Output of CB2

The input terminals of TL2 are connected to the output terminals of the 200 A distribution panel. The electric circuit schematic of the first two sections of TL2 is shown in Fig. 15. The last two sections are shown in Fig. 16. TL2 represents a 20-foot-long physical transmission line of four No. 2 AWG insulated phase and neutral conductors and a bare No. 2 AWG conductor in a 1.5-inch-diameter EMT conduit. The bare conductor serves as the ground conductor. The ground line and a neutral both exist in the model, but circuit components are present only for the three phase conductors. These components consist of three shunt capacitances, three series resistances, and three series inductances for each T-section of TL2. The input terminals of TL2 are labeled “20FTL_XIn,” where X = A, B, C, N, or G.

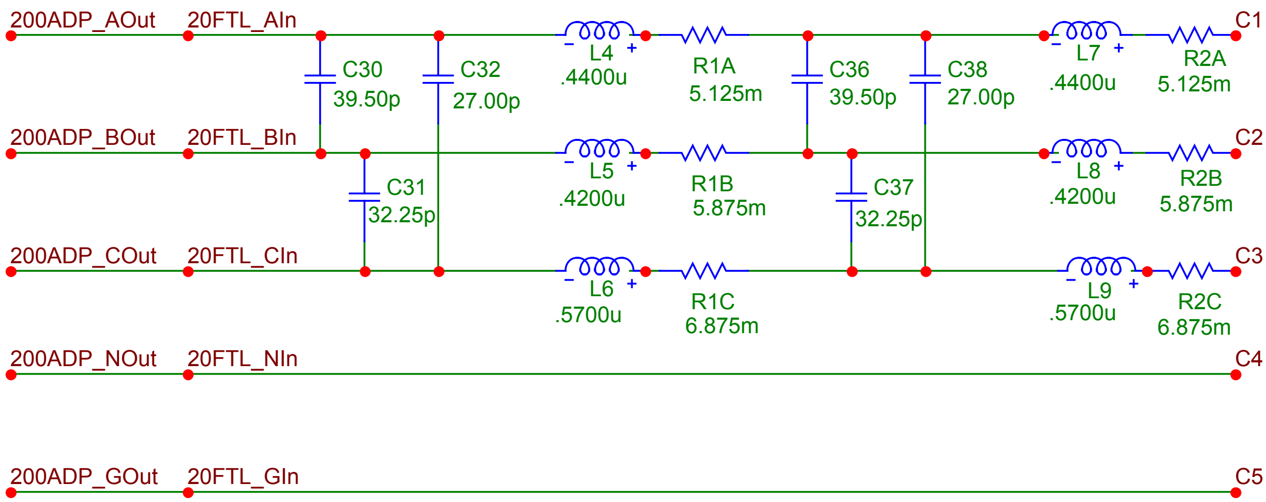


Figure 15. Electric Circuit Schematic of the First Two Sections of TL2

The connections to the 200 A distribution panel model terminals are shown at the left. The connections to the last two sections of TL2 are shown at the right.

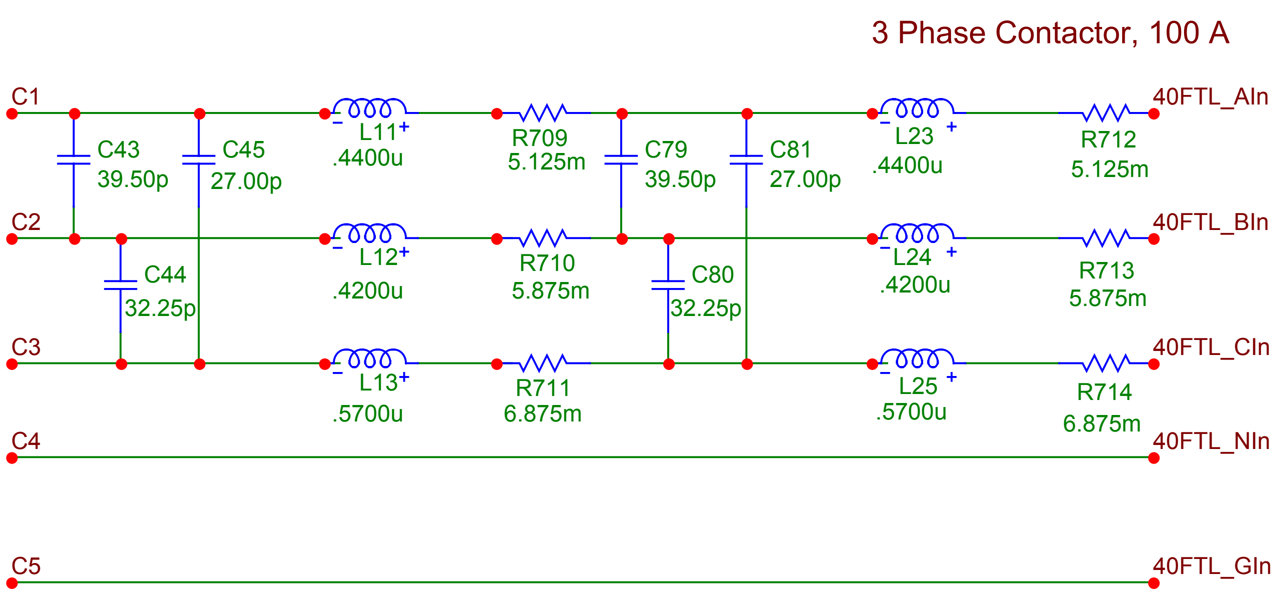


Figure 16. Electric Circuit Schematic of the Last Two Sections of TL2

The connections to the fist two sections of TL2 are shown at the left. The connections to TL3 are shown at the right.

The output terminals of TL2 connect to the input terminals of TL3. The electric circuit schematic of the first two sections of TL3 is shown in Fig. 17. The last two sections are shown in Fig. 18. The input terminals of TL3 are labeled "40FTL_XIn," where X = A, B, C, N, or G. This model represents a 40-foot-long transmission line composed of four insulated No. 2 AWG conductors and one bare No. 2 AWG conductor in a 1.5-inch-diameter EMT conduit. Three of the insulated conductors are the phase conductors, and one of the insulated conductors is the neutral conductor. The bare conductor is the ground conductor. Each T-section of this model has nine shunt capacitances. For this transmission line model, the neutral-to-ground shunt capacitances are non-existent. The series inductances and resistances exist for each line, except the neutral line. The connection points of the TL2 and TL3 represent a three-phase, 100 A contactor. It is labeled "3 Phase Contactor, 100 A."

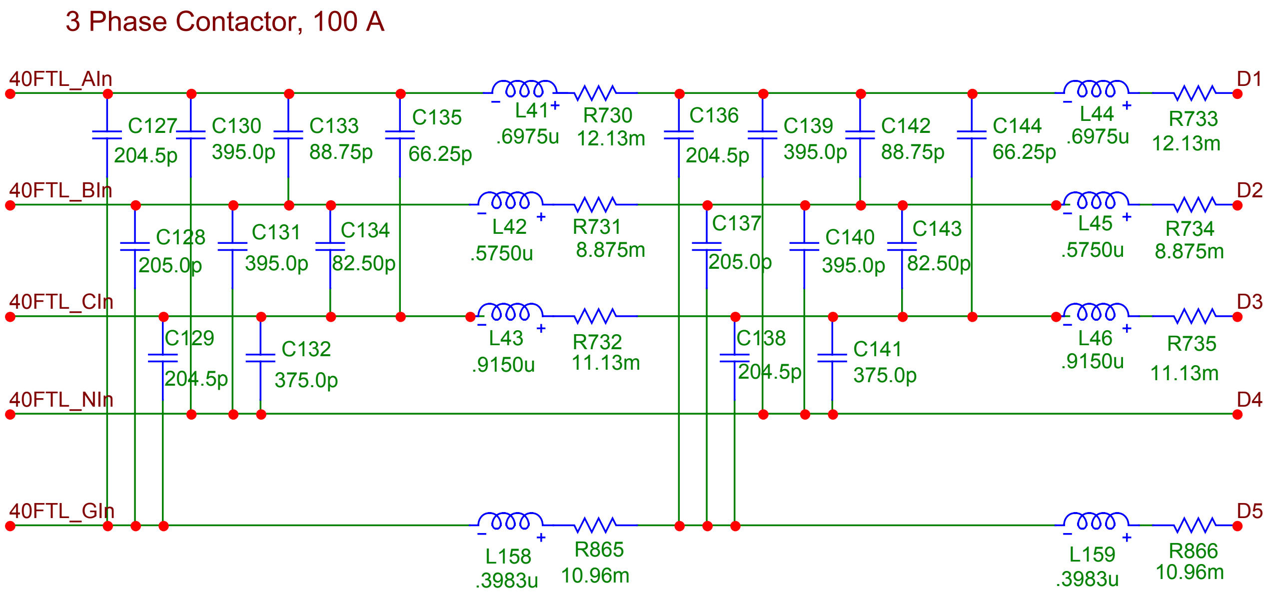


Figure 17. Electric Circuit Schematic of the First Two Sections of TL3

The connections to TL2 are shown at the left. The connections to the last two sections of TL3 are shown at the right.

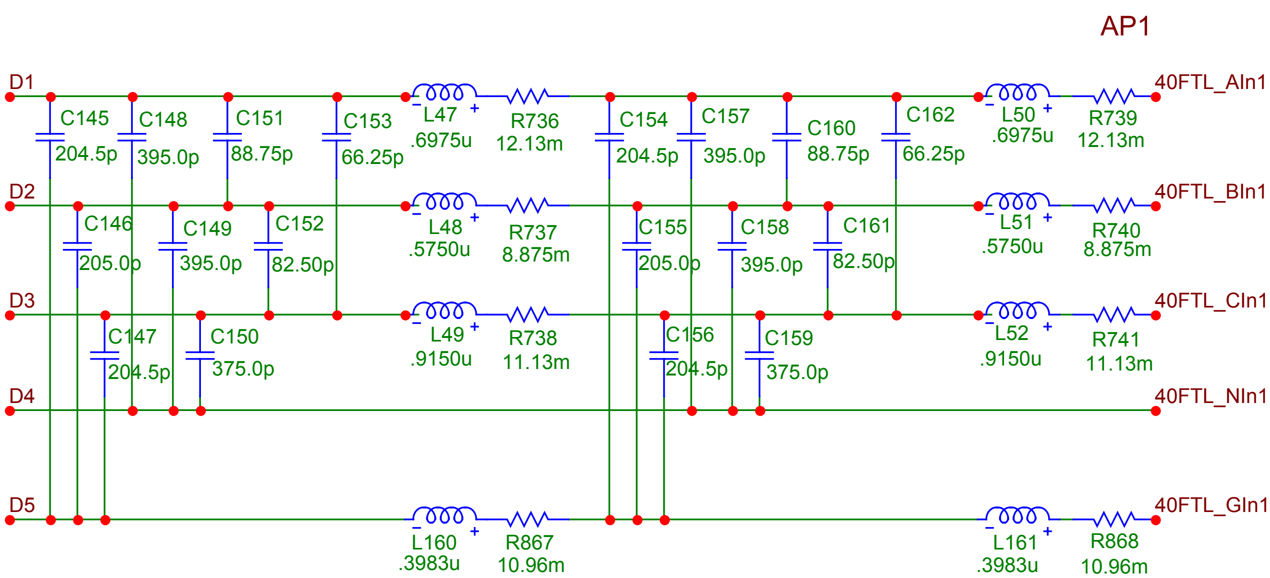


Figure 18. Electric Circuit Schematic of the Last Two Sections of TL3

The connections to the fist two sections of TL3 are shown at the left. The connections to TL4 are shown at the right.

The output terminals of TL3 connect to the input terminals of TL4 at Attachment Point 1, identified by "AP1" on the circuit schematic. The electric circuit schematic of the first two sections of TL4 is shown in Fig.19. The last two sections are shown schematically in Fig. 20. The input terminals of TL4 are labeled "40FTL_XIn1," where X = A., B, C, N, or G. This model represents another physical transmission line with the same construction as the third transmission line. The full set of model T-section circuit components is present.

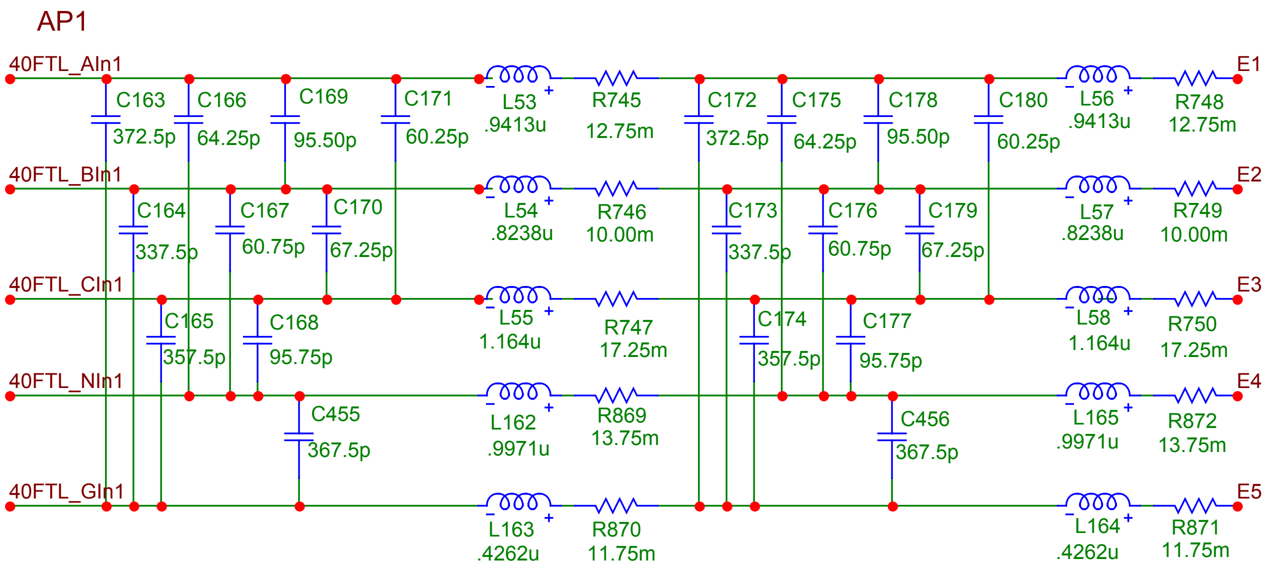


Figure 19. Electric Circuit Schematic of the First Two Sections of TL4

The connections to TL3 are shown at the left. The connections to the last two sections of TL4 are shown at the right.

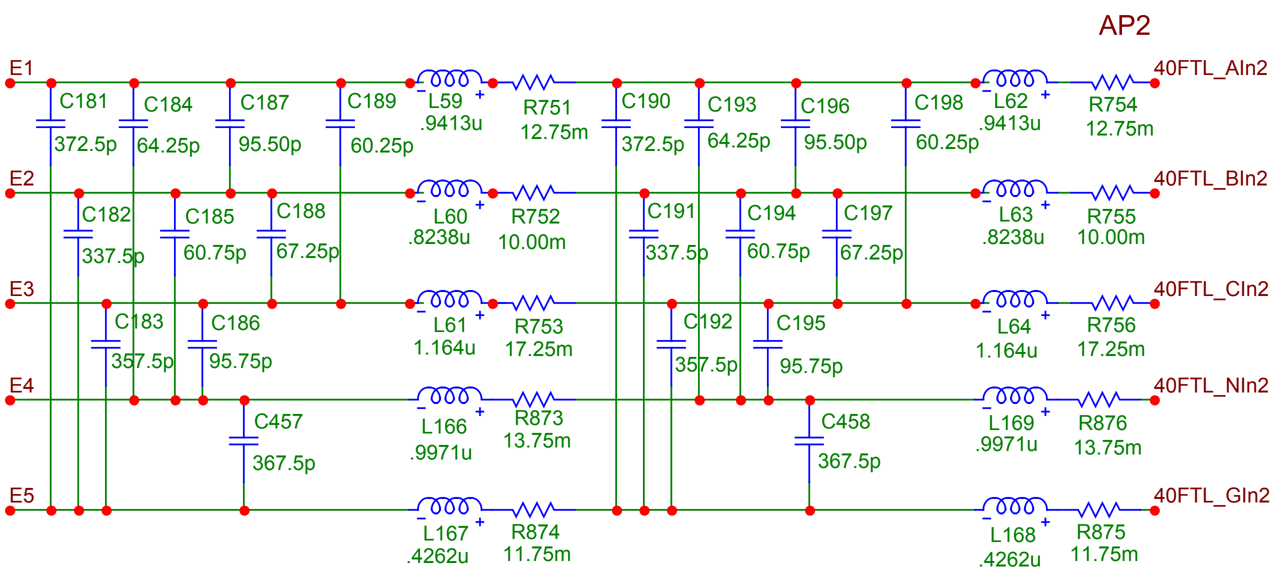


Figure 20. Electric Circuit schematic of the Last Two Sections of TL4

The connections to the fist two sections of TL4 are shown at the left. The connections to TL5 are shown at the right.

The output terminals of TL4 connect to the input terminals of TL5 at Attachment Point 2, which is identified by "AP2" on the circuit schematic. The electric circuit schematic of the first two sections of TL5 is shown in Fig. 21, while the last two sections are shown schematically in Fig. 22. The input terminals of TL5 are labeled "40FTL_XIn2," where X = A, B, C, N, or G. This transmission line model has the full set of circuit components. This model represents another 40-foot-long transmission line of the same construction as the previous transmission line.

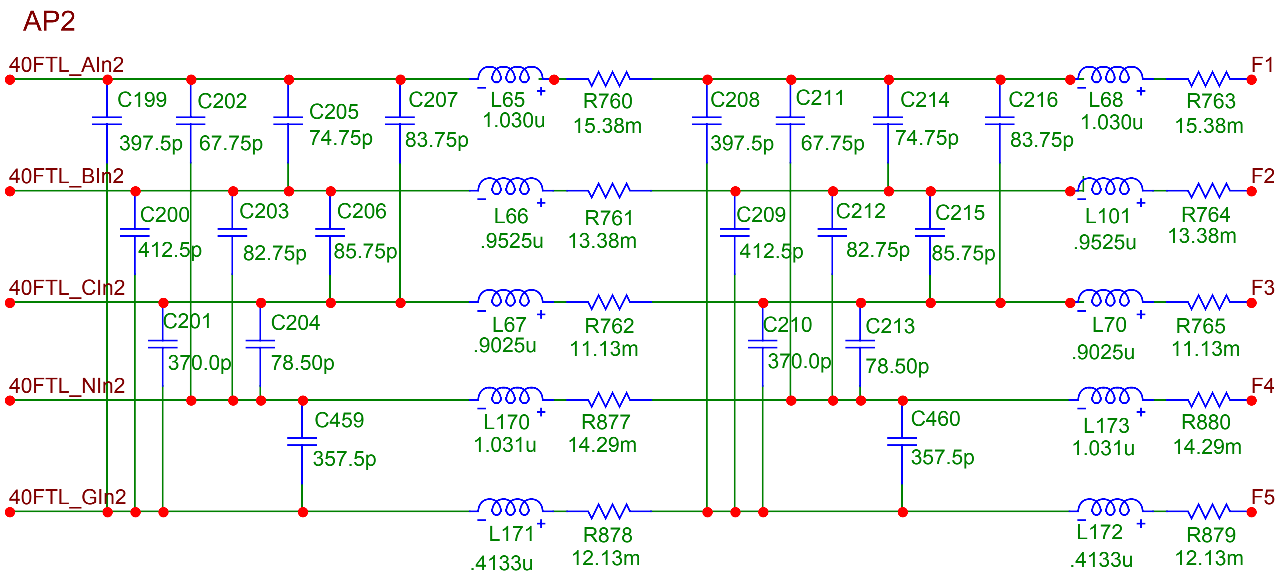


Figure 21. Electric Circuit Schematic of the First Two Sections of TL5

The connections to TL4 are shown at the left. The connections to the last two sections of TL5 are shown at the right.

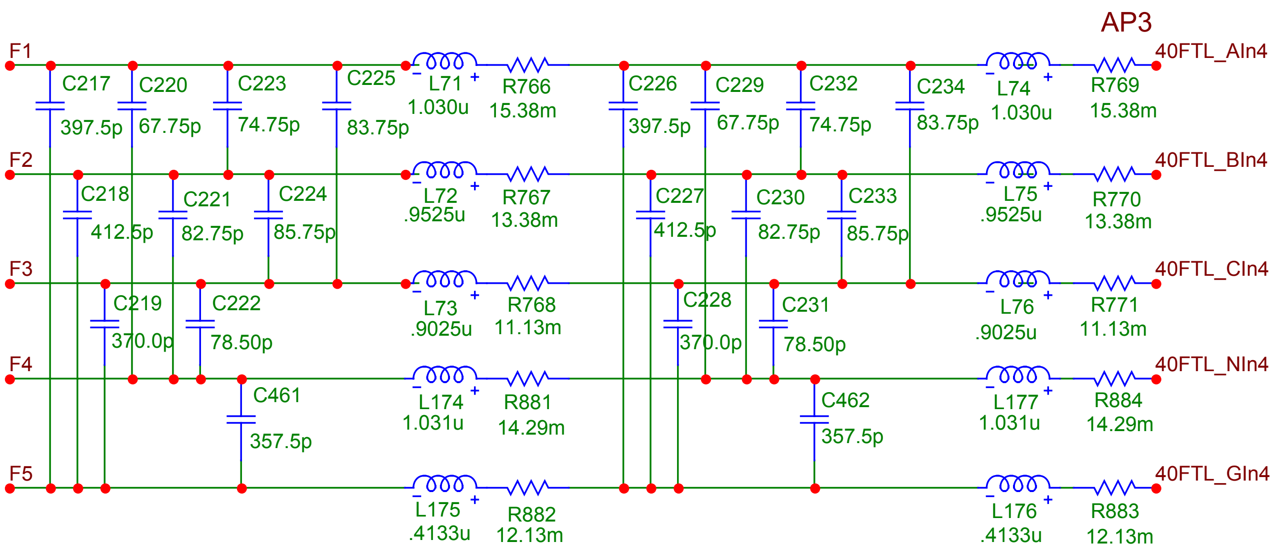


Figure 22. Electric Circuit Schematic of the Last Two Sections of TL5

The connections to the fist two sections of TL5 are shown at the left. The connections to TL6 are shown at the right.

The output terminals of TL5 connect to the input terminals of TL6 at Attachment Point 3, which is labeled “AP3” on the circuit schematic. The electric circuit schematic of the first two sections of TL6 is shown in Fig. 23, while the last two sections of TL6 are shown schematically in Fig. 24. The input terminals of TL6 are identified as “40FTL_XIn4,” where X = A, B, C, N, or G. This model has the full set of T-section circuit components. It represents a physical transmission line that is 40 feet in length and has the same construction as the previous transmission line. The output terminals of TL6 are connected to the input terminals of the 100 A distribution panel, which are labeled “100ADP_XIn,” where X = A, B, C, X, N, or G.

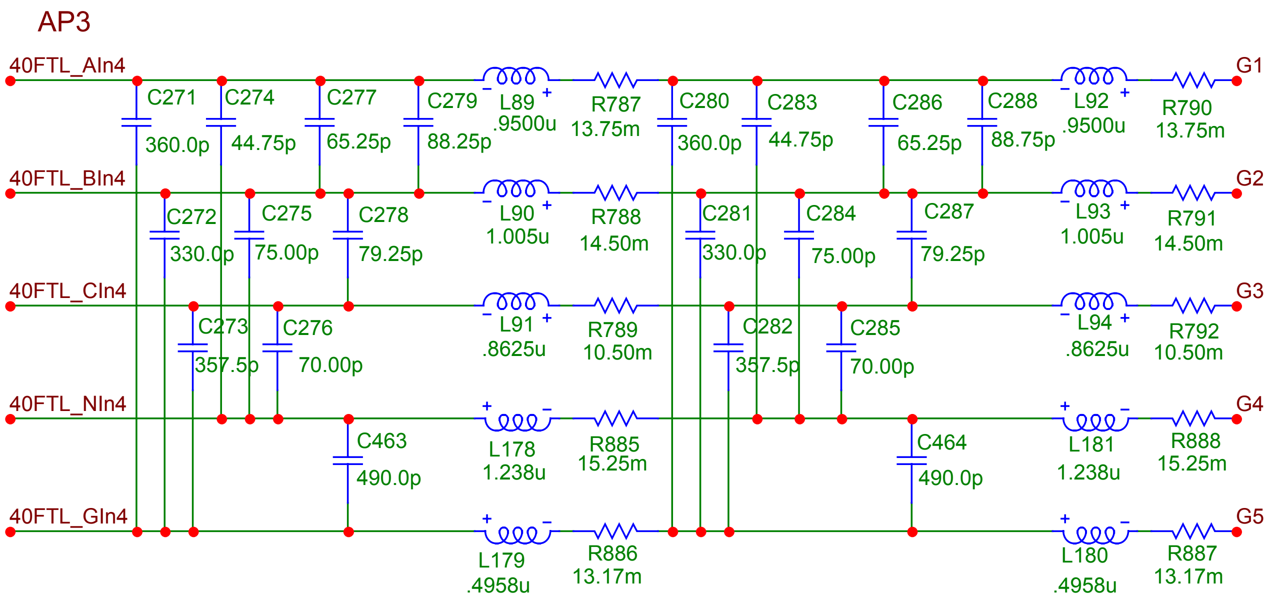


Figure 23. Electric Circuit Schematic of the First Two Sections of TL6

The connections to TL5 are shown at the left. The connections to the last two sections of TL6 are shown at the right.

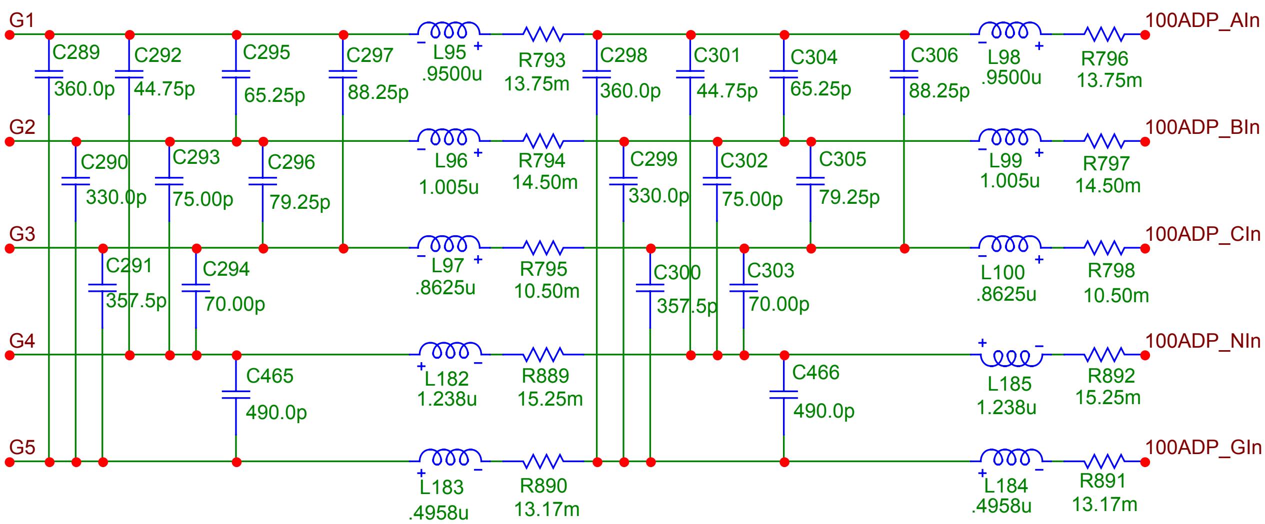


Figure 24. Electric Circuit Schematic of the Last Two Sections of TL6

The connections to the fist two sections of TL6 are shown at the left. The connections to the input of the 100 A Distribution Panel model are shown at the right.

The electric circuit schematic of the 100 A distribution panel model is shown in Fig. 25. This model is described in greater detail in the subsequent section entitled "The 100 A Distribution Panel Model." The waveforms of the phase voltages at the input to the 100 A distribution panel model, which is the input to CB8, are shown in the top frame of Fig. 26. The A phase voltage is labeled "V(100ADP_AIn)," the B phase voltage is labeled "V(100ADP_BIn)," and the C phase voltage is labeled "V(100ADP_CIn)." The phase currents at the input to this model are shown in the bottom frame of the same figure. The A phase current is labeled "I(R796)." The B phase current is labeled as "I(R797)," and the C phase current is labeled as "I(R798)." The waveforms of the phase voltages at the upper output of the 100 A distribution panel model, which is also the output from CB9, are presented in the top frame of Fig. 27. The A phase voltage is labeled “V(100ADP_A20Out),” the B phase voltage is labeled “V(100ADP_B20Out),” and the C phase voltage is labeled “V(100ADP_C20Out).” The phase currents at the upper output of this model are shown in the bottom frame of the same figure. The A phase current is labeled “I(VA).” The B phase current is labeled as “I(VB),” and the C phase current is labeled as “I(VC).” The waveforms of the phase voltages at the lower output of the 100 A distribution panel model, which is also the output from CB10, are presented in the top frame of Fig. 28. The A phase voltage is labeled “V(100ADP_A60Out),” the B phase voltage is labeled “V(100ADP_B60Out),” and the C phase voltage is labeled “V(100ADP_C60Out).” The phase currents at the lower output of the model are shown in the bottom frame of the same figure. The A phase current is labeled “I(VA).” The B phase current is labeled as “I(VB),” and the C phase current is labeled as “I(VC).”

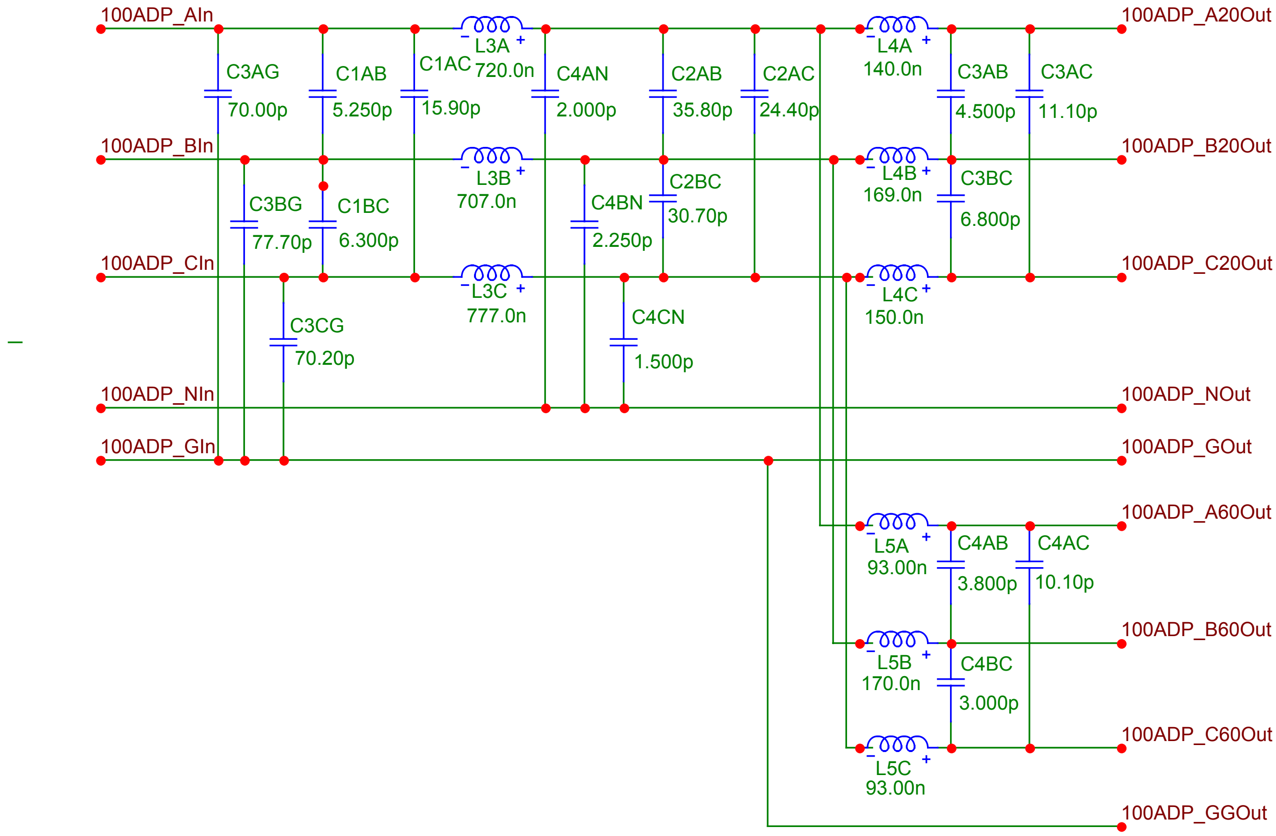


Figure 25. Electric Circuit Schematic of the 100 A Distribution Panel Model

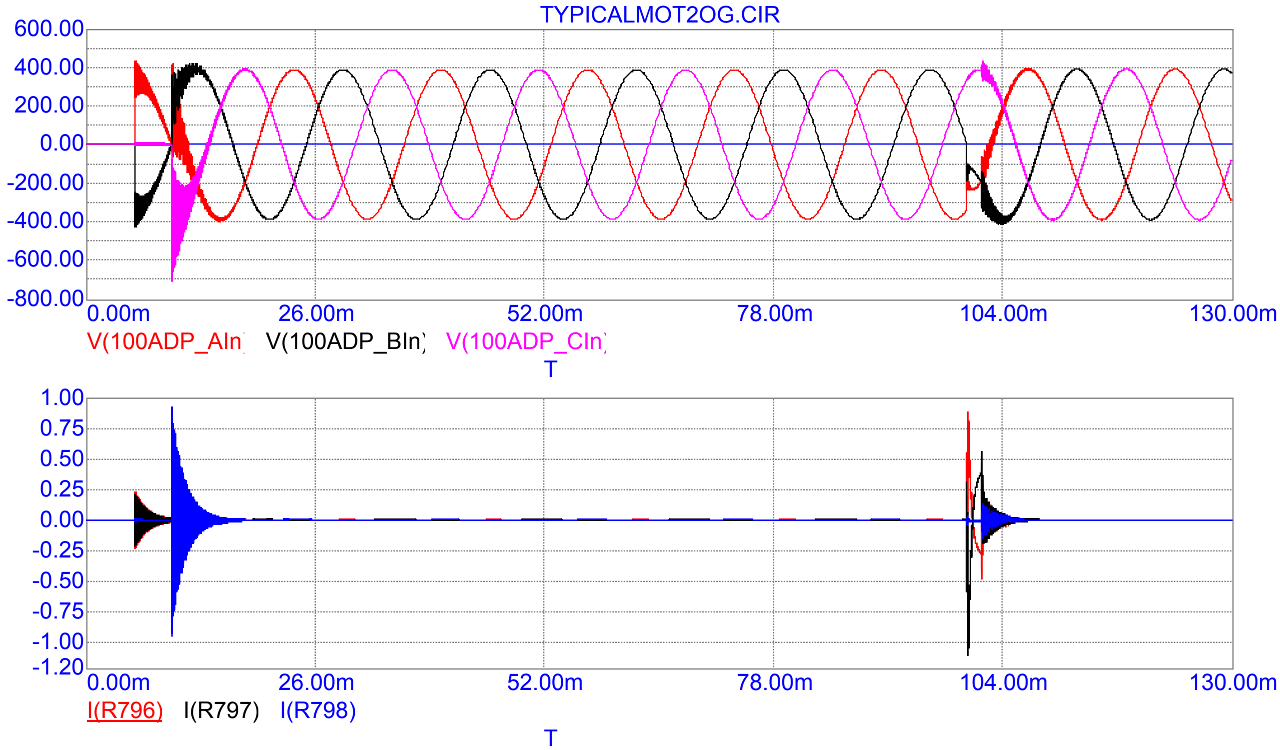


Figure 26. Phase Voltages and Currents at the Input to CB8

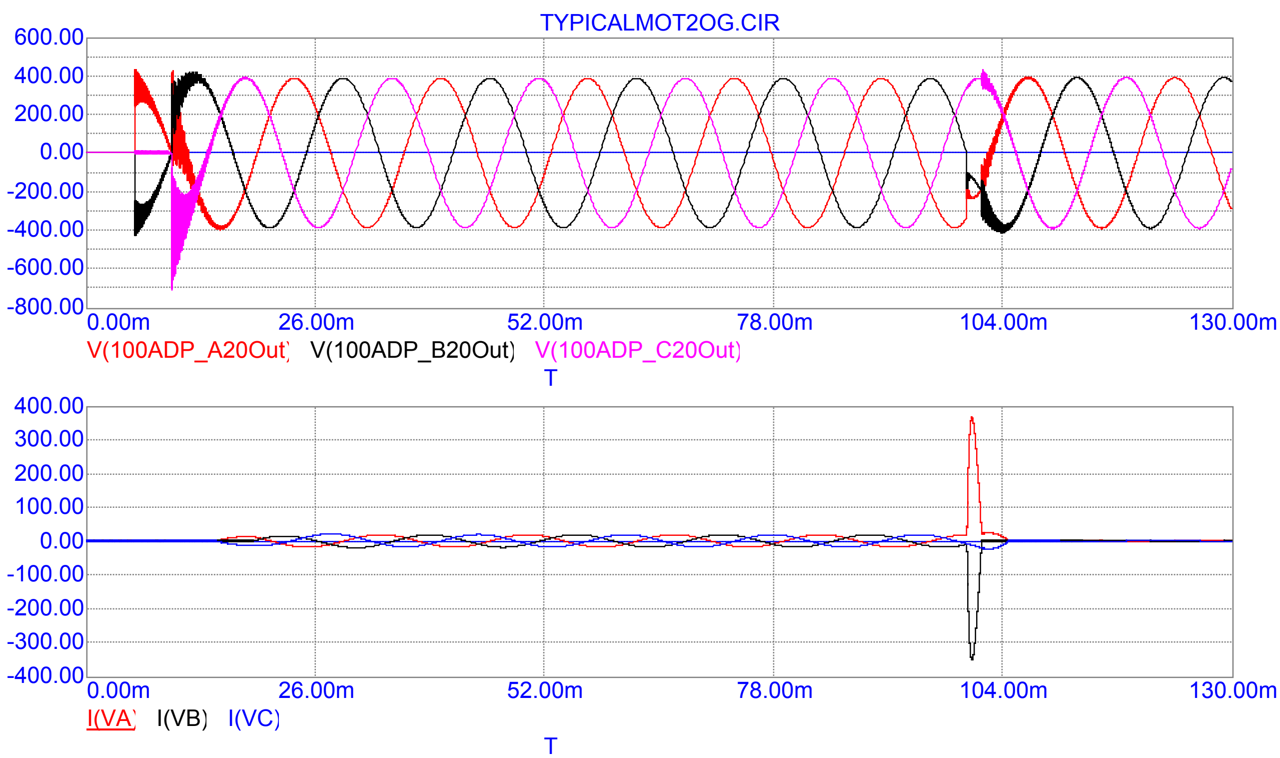


Figure 27. Phase Voltages and Currents at the Output from CB9

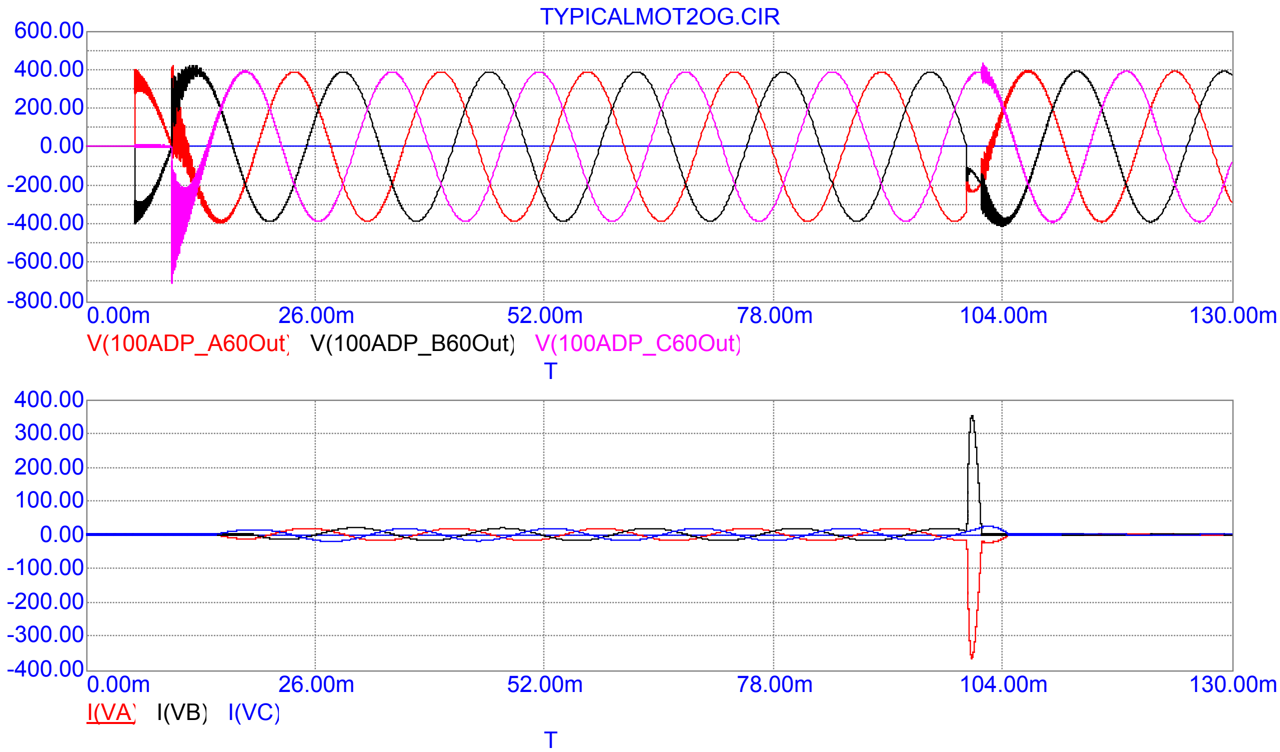


Figure 28. Phase Voltages and Currents at the Output from CB10

The inputs to TL7 are connected to the upper output terminals of the 100 A distribution panel. The electric circuit schematic of the first two sections of TL7 is shown in Fig. 29, while the last two sections are shown schematically in Fig. 30. These output terminals of the 100 A distribution panel are labeled “100ADP_X20Out,” where X = A, B, C, N, or G. The input terminals to TL7 are identified as “40FTL_XIn,” where X = A, B, C, N, or G. The seventh transmission line model represents a 40-foot-long transmission line, composed of four insulated No. 10 AWG conductors and one bare No. 10 AWG conductor in an 0.75-inch-diameter EMT conduit. The bare conductor is the ground conductor. This transmission line model has the full set of T-section circuit components. The waveforms of the phase voltages at the input to TL7 are presented in the top frame of Fig. 27. The A phase voltage is labeled “V(100ADP_A20Out),” the B phase voltage is labeled “V(100ADP_B20Out),” and the C phase voltage is labeled “V(100ADP_C20Out).” Similarly, the phase currents at the input to TL7 are shown in the bottom frame of the same Fig. 27. The A phase current is labeled “I(VA).” The B phase current is labeled as “I(VB),” and the C phase current is labeled as “I(VC).”

The waveforms of the phase voltages at the output of TL7 are displayed in the top frame of Fig. 31. The A phase voltage is designated as “V(40FTL_AIn3).” The B phase voltage is designated as “V(40FTL_BIn3).” Similarly, the C phase voltage is designated as “V(40FTL_CIn3).” The waveforms of the phase currents at the output of TL7 are shown in the bottom frame of Fig. 31. The A phase current is I(R715), the B phase current is I(R716), and the C phase current is I(R717).

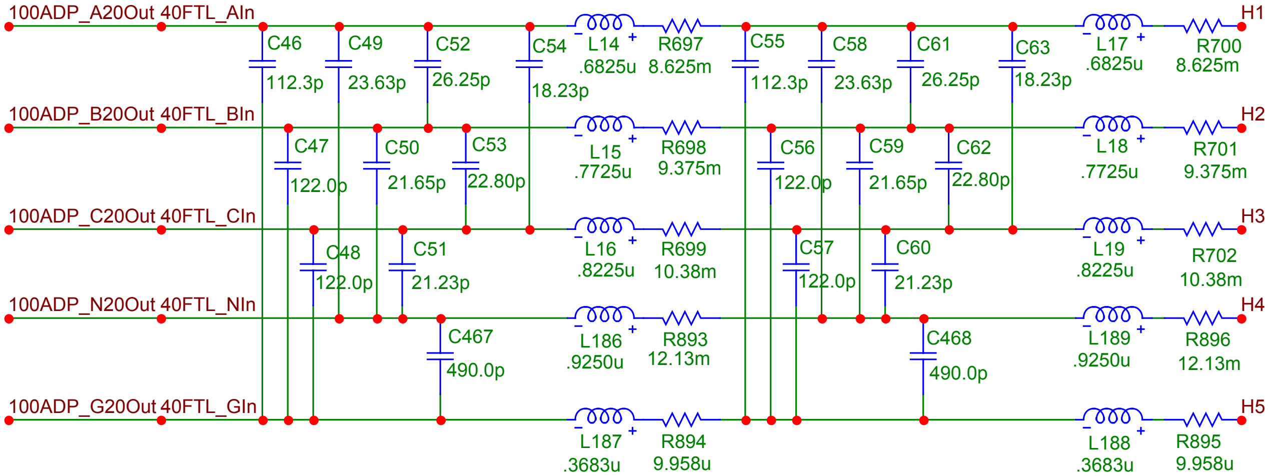


Figure 29. Electric Circuit Schematic of the First Two Sections of TL7

The connections to CB8 are shown at the left. The connections to the last two sections of TL7 are shown at the right.

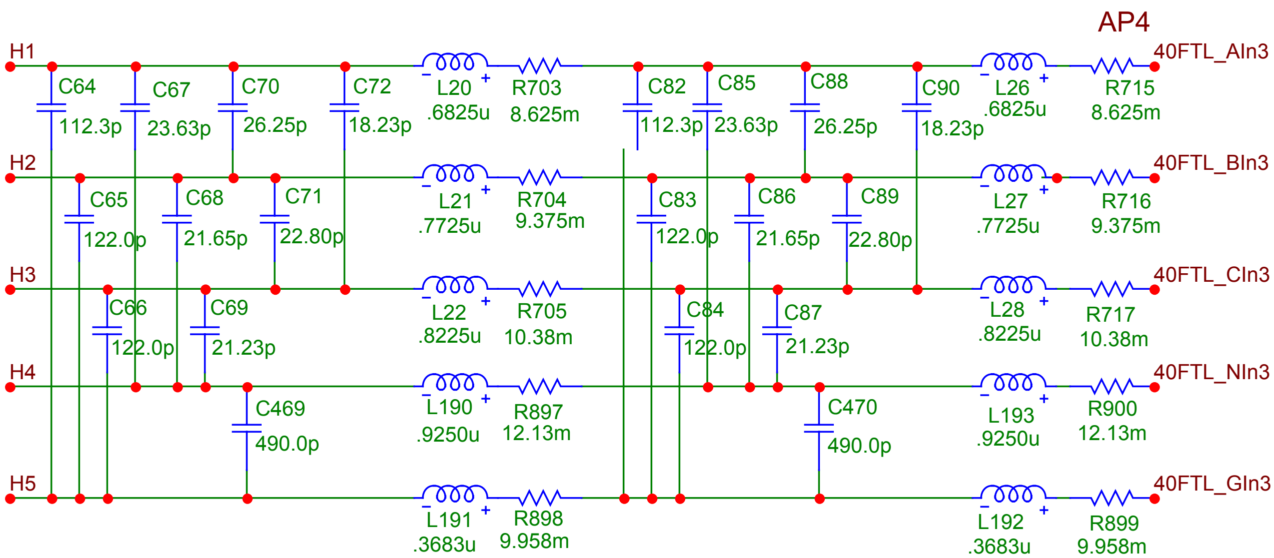


Figure 30. Electric Circuit Schematic of the Last Two Sections of TL7

The connections to the fist two sections of TL7 are shown at the left. The connections to TL8 are shown at the right.

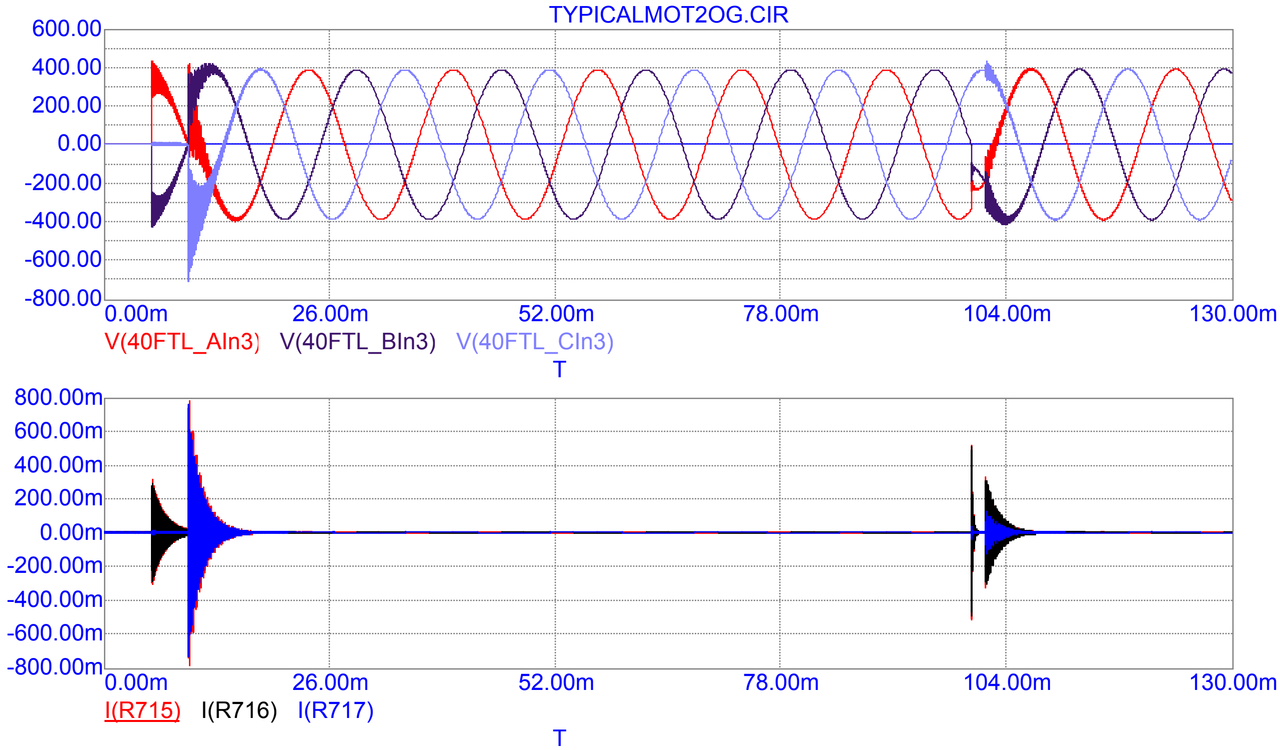


Figure 31. Phase Voltages and Currents at the Output of TL7

The output terminals of TL7 connect to the input terminals of TL8 at Attachment Point 4, labeled “AP4” on the circuit schematic. The electric circuit schematic of TL8 is shown in Fig. 32 and Fig. 33. The A phase lamp model, R706, is also shown in Fig. 33. The input terminals of TL8 are identified as “40FTL_XIn3,” where X = A, B, C, N, or G. TL8 has almost the full set of T-section circuit components – it is missing the A phase-to-neutral shunt capacitances. This transmission line model represents another 40-foot-long transmission line with the same construction as the previous one. The A phase output terminal of TL8 connects to a series resistance, R706, which represents the A phase fluorescent lamps in front of Attachment Point 5. R706 has a resistance of 1 Ohm. It is labeled “A Phase lamp” on the circuit schematic. Attachment Point 5 is labeled “AP5.” The phase quantity waveforms at the input to TL8 are shown in Fig. 31. The corresponding waveforms at the output of TL8 are shown in Fig. 34. The A phase voltage is V(128), the B phase voltage is V(40FTL_BIn5), and the C phase voltage is V(40FTL_CIn5). The A phase current is I(R826), the B phase current is I(R827), and the C phase current is I(R828).

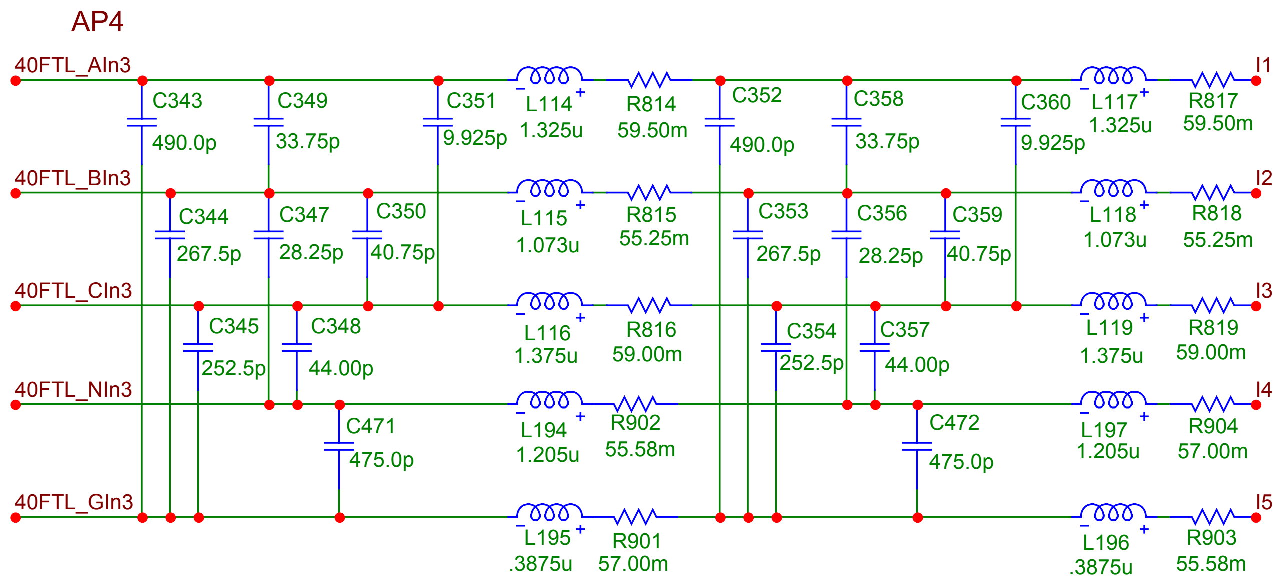


Figure 32. Electric Circuit Schematic of the First Two Sections of TL8

The connections to TL7 are shown at the left. The connections to the last two sections of TL8 are shown at the right.

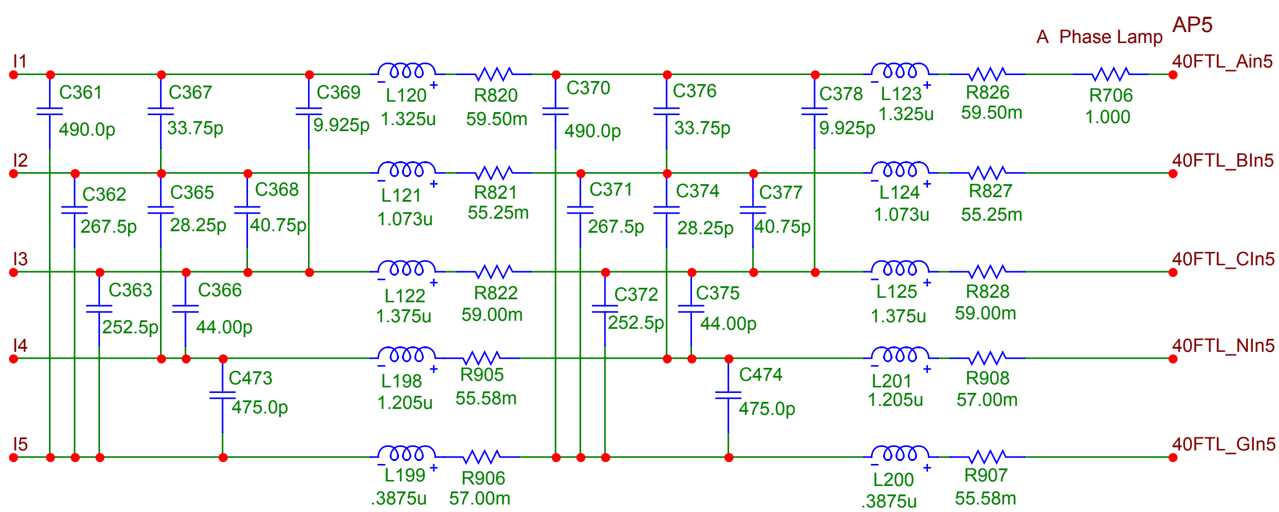


Figure 33. Electric Circuit Schematic of the Last Two Sections of TL8

The connections to the first to sections of TL8 are shown at the left. The connections to TL9 are shown at the right. The A phase lamp resistor R706 is connected to R826.

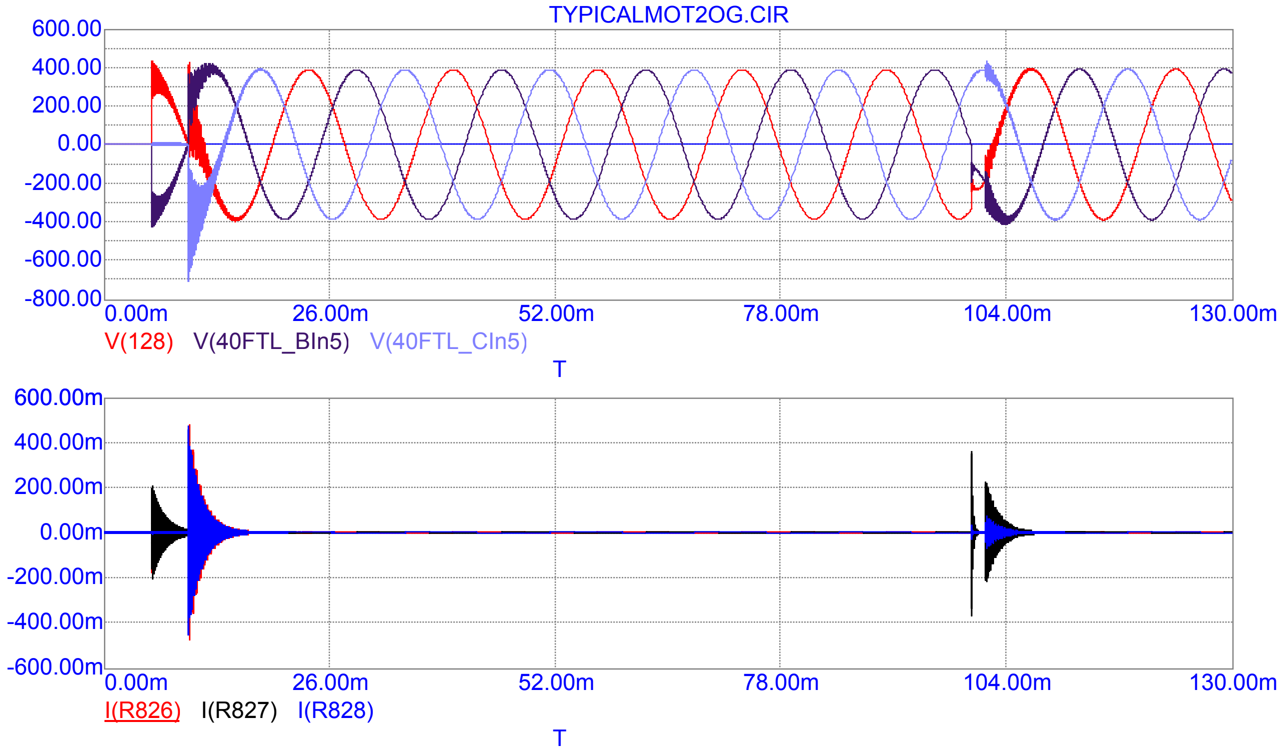


Figure 34. Phase Voltages and Currents at the Output from TL8

The A phase input terminal of TL9 is connected to the output side of R706, whereas all the other input terminals of TL9 are connected to the corresponding output terminals of the eighth transmission line model at Attachment Point 5. Attachment Point 5 is labeled “AP5” on the schematic for the circuit. The electric circuit schematic of TL9 is shown in Fig. 35 and Fig. 36. The B phase lamp model, R824, is also shown in Fig. 36. The input terminals to TL9 are shown as “40FTL_XIn5,” where X = A, B, C, N, or G. This transmission line model represents yet another 40-foot-long transmission line with the same construction as the previous transmission line. This model also has almost the full set of T-section components. The B phase-to-neutral shunt capacitances are missing. The phase voltage and current waveforms at the output of TL9 are shown in Fig. 37. The A phase voltage is V(40FTL_AIn6), the B phase voltage is V(341), and the C phase voltage is V(40FTL_CIn6). The A phase current is I(R838), the B phase current is I(R839), and the C phase current is I(R840).

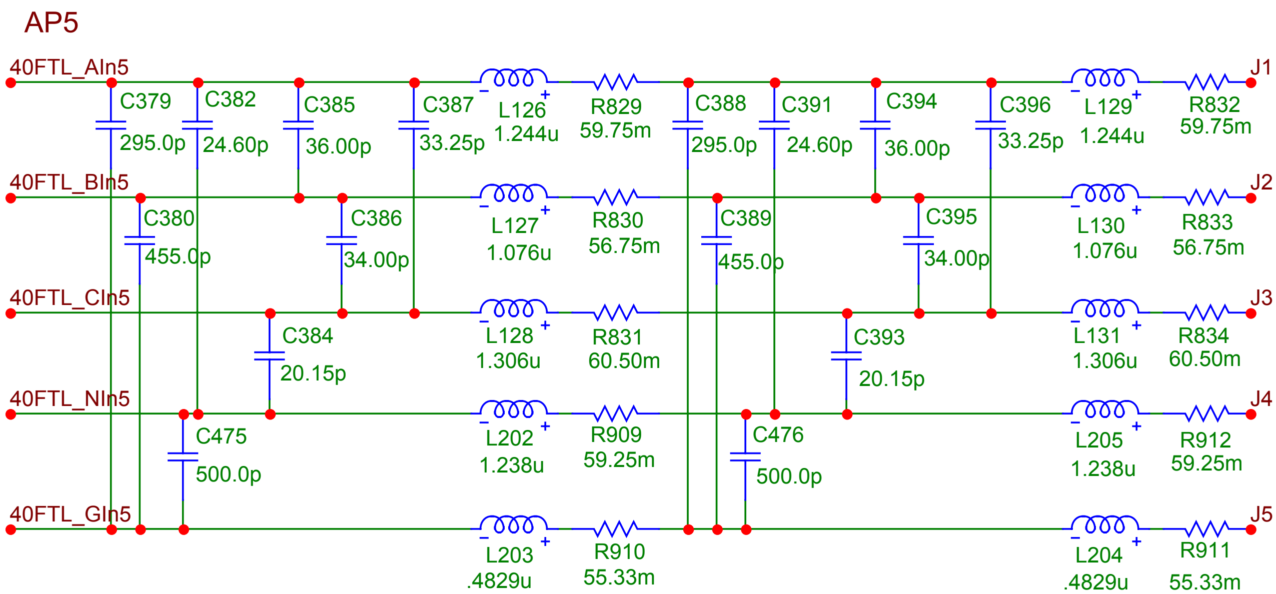


Figure 35. Electric Circuit Schematic of the First Two Sections of TL9

The connections to the A phase lamp model and TL8 are shown at the left. The connections to the last two sections of TL9 are shown at the right.

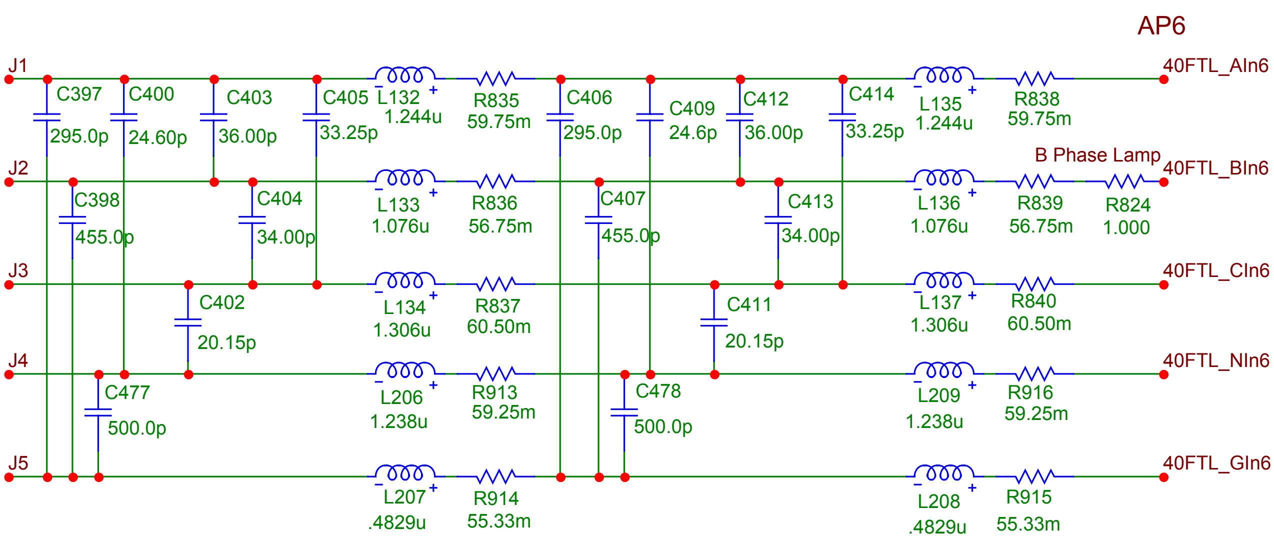


Figure 36. Electric Circuit Schematic of the Last Two Sections of TL9

The connections to the first two sections of TL9 are shown at the left. The connections to TL10 are shown at the right. The B phase lamp resistor R824 is connected to R839.

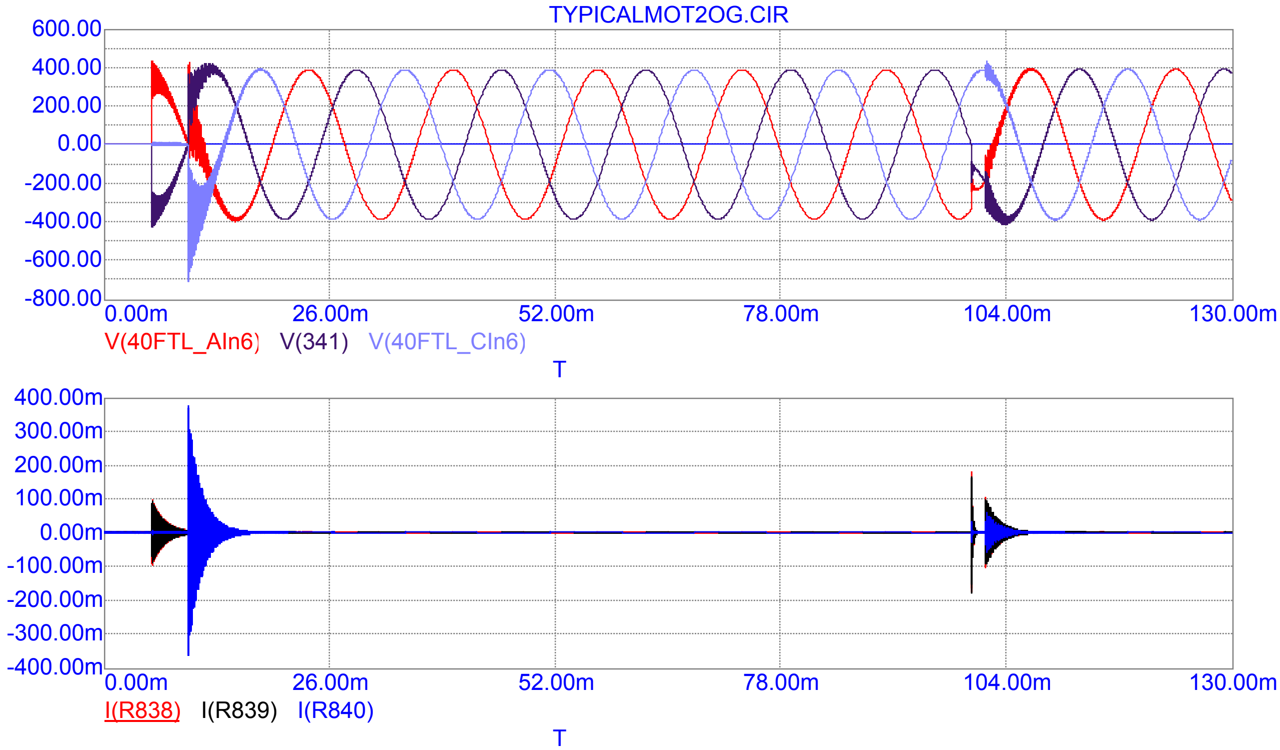


Figure 37. Phase Voltages and Currents at the Output from TL9

The output from R824 connects to the B phase input terminal of TL10 at Attachment Point 6, designated as "AP6" on the circuit schematic. The other outputs from TL9 connect to the corresponding input terminals of TL10. The electric circuit schematic of TL10 is shown in Fig. 38 and Fig. 39. The C phase lamp model, R841, is also shown in Fig. 39. The three-phase termination resistors, which represent an open circuit, are shown at the right of Fig. 39. The input terminals of TL10 are shown as "40FTL_XIn6," where X = A, B, C, N, or G. TL10 represents another transmission line of 40-foot length with the same construction as the prior one. TL10 has almost the full complement of T-section circuit components, since the C phase-to-neutral shunt capacitances are absent. The C phase output terminal from TL10 connects to the resistor, R841, which models the C phase fluorescent lamps. R841 has a value of 1 Ohm. The phase voltage and current waveforms at the output of TL10 are shown in Fig. 40. The A phase voltage is V(409), the B phase voltage is V(410), and the C phase voltage is V(381). The A phase current is I(R851), the B phase current is I(R852), and the C phase current is I(R853).

The output terminal from R841 connects to the C phase resistance, R856, of a three-phase termination resistor array at Attachment Point 7. This attachment point is labeled "AP7" on the circuit schematic. The output terminals for the A and B phase lines of TL10 connect to resistors, R854 and R855, respectively. The neutral output terminal of TL10 connects to the resistance, R945. The four resistors – R854, R855, R856, and R945 – have values of 10 GOhms. They represent an open circuit at Attachment Point 7. The output sides of these four resistors are connected together. The ground output terminal of the tenth transmission line model is connected to a ground symbol, indicating the circuit ground.

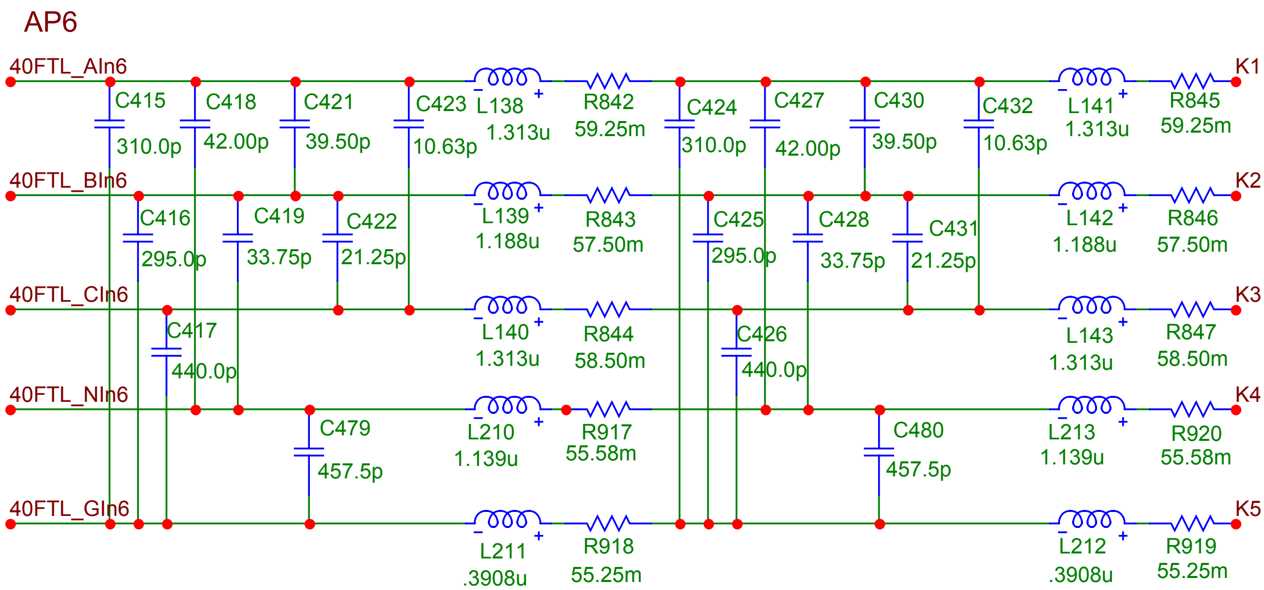


Figure 38. Electric Circuit Schematic of the First Two Sections of TL10

The connections to the B phase lamp model and TL9 are shown at the left. The connections to the last two sections of TL10 are shown at the right.

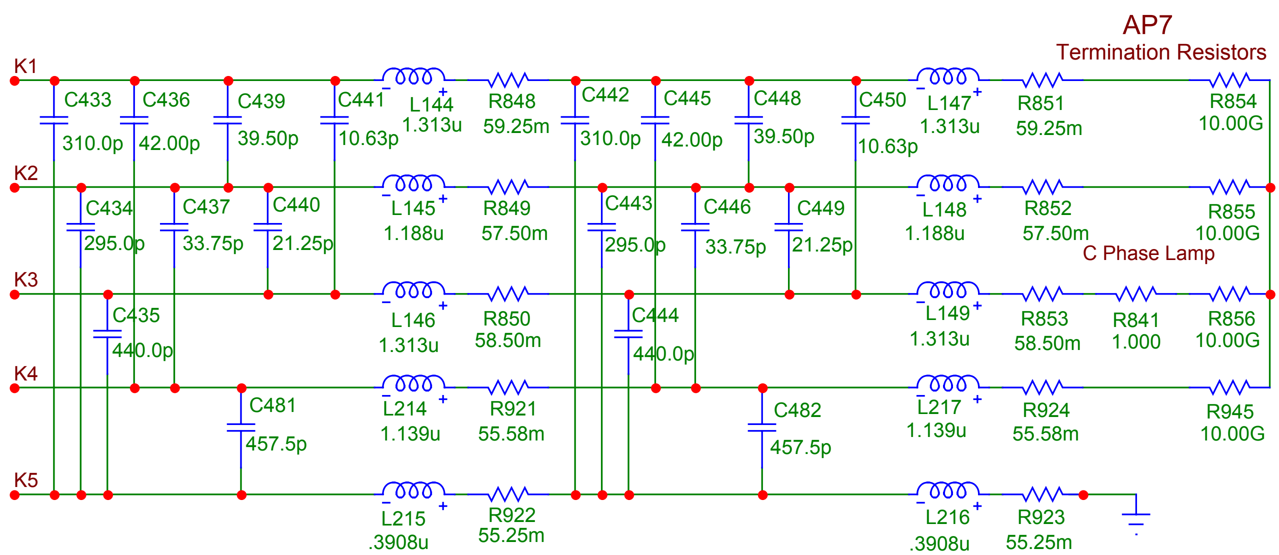


Figure 39. Electric Circuit Schematic of the Last Two Sections of TL10

The connections to the first two sections of TL10 are shown at the left. The connections to the C phase lamp model, the ground connection, and the termination resistor bank are shown at the right. The C phase lamp resistor R841 is connected to R853.

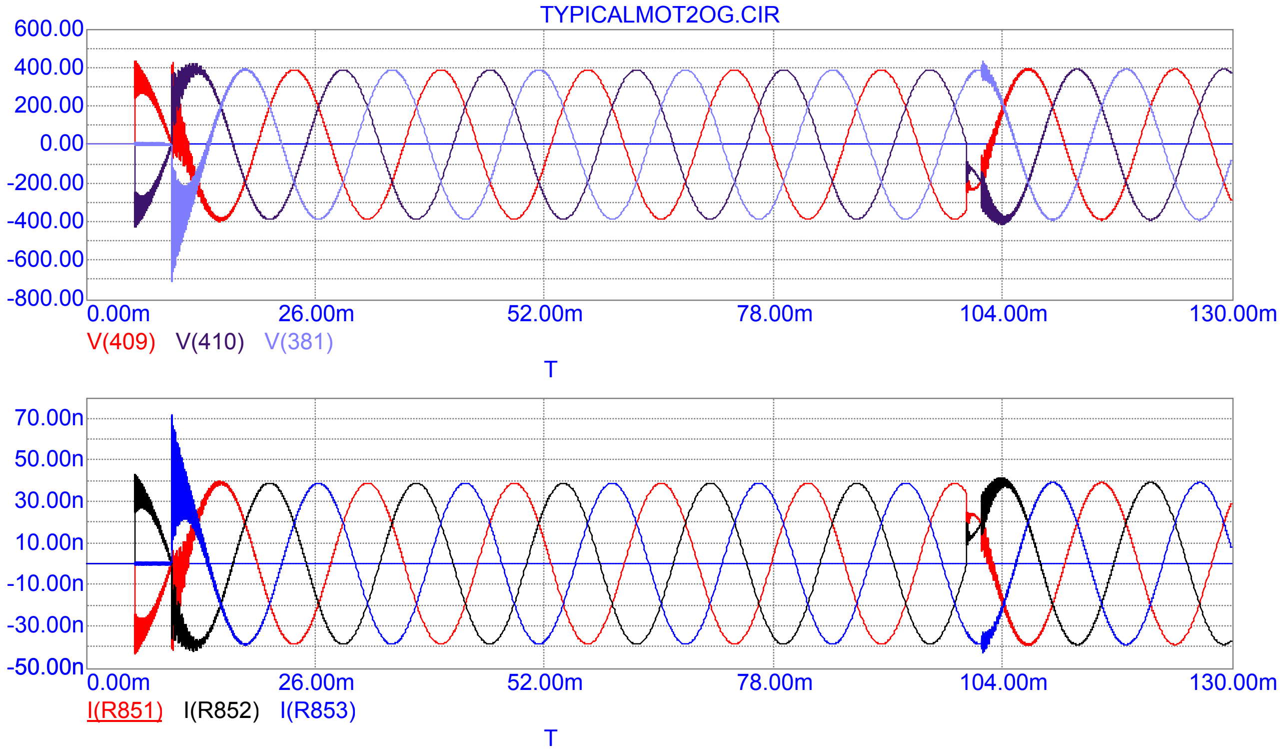


Figure 40. Phase Voltages and Currents at the Output from TL10

The input terminals to TL11 are connected to the lower set of output terminals from the 100 A distribution panel, which are the outputs from CB10. The electric circuit schematic of TL11 is shown in Fig. 41 and Fig. 42. The three distribution panel terminals are labeled "100ADP_X60Out," where X = A, B, or C, for the phase lines. The neutral line is absent from these outputs. A ground line is carried out in the model schematic. It is labeled "100ADP_G60Out" in Fig. 25. TL11 has three phase terminals and one ground terminal at the input. These terminals are labeled "80FTL_XIn," where X = A, B, C, or G. The usual neutral line is absent. This model has six shunt capacitances, four series resistances, and four series inductances per T-section, which constitutes a full set of T-section components for this type of four-wire transmission line model. This model represents an 80-foot-long transmission line composed of three insulated No. 6 AWG conductors and one bare No. 6 AWG conductor in a 1.5-inch-diameter EMT conduit. The phase voltage and current waveforms at the output from TL11 are shown in Fig. 43. The A phase voltage is V(80FTL_AIn1), the B phase voltage is V(80FTL_BIn1), and the C phase voltage is V(80FTL_CIn1). The A phase current is I(R811), the B phase current is I(R812), and the C phase current is I(R813).

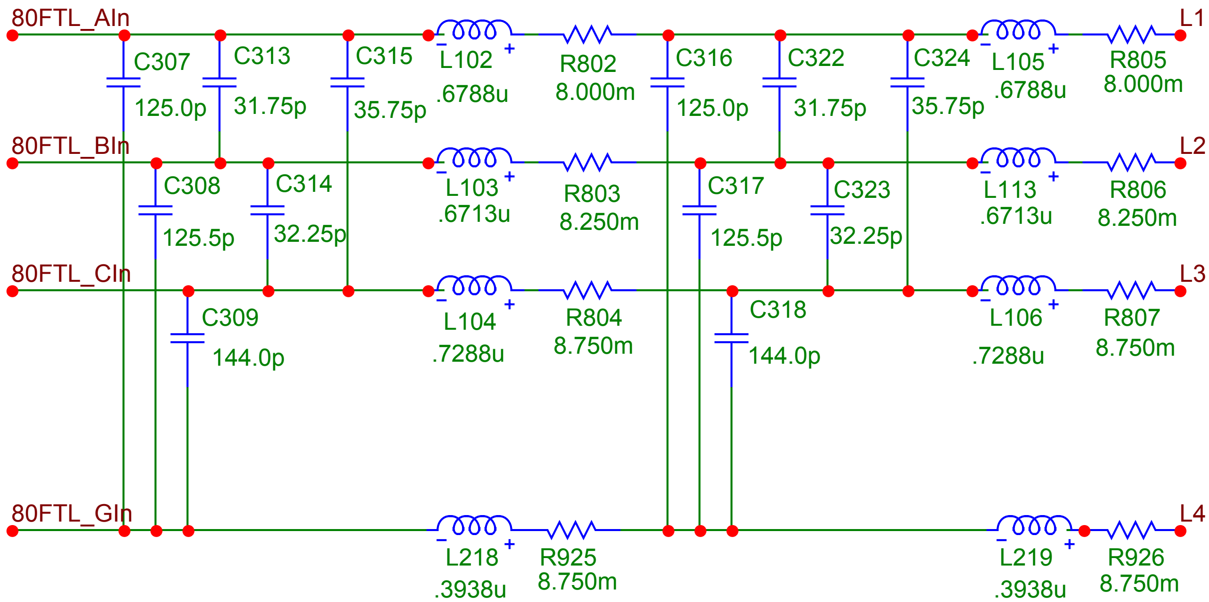


Figure 41. Electric Circuit Schematic of the First Two Sections of TL11

The connections to CB9 are shown at the left. The connections to the last two sections of TL11 are shown at the right.

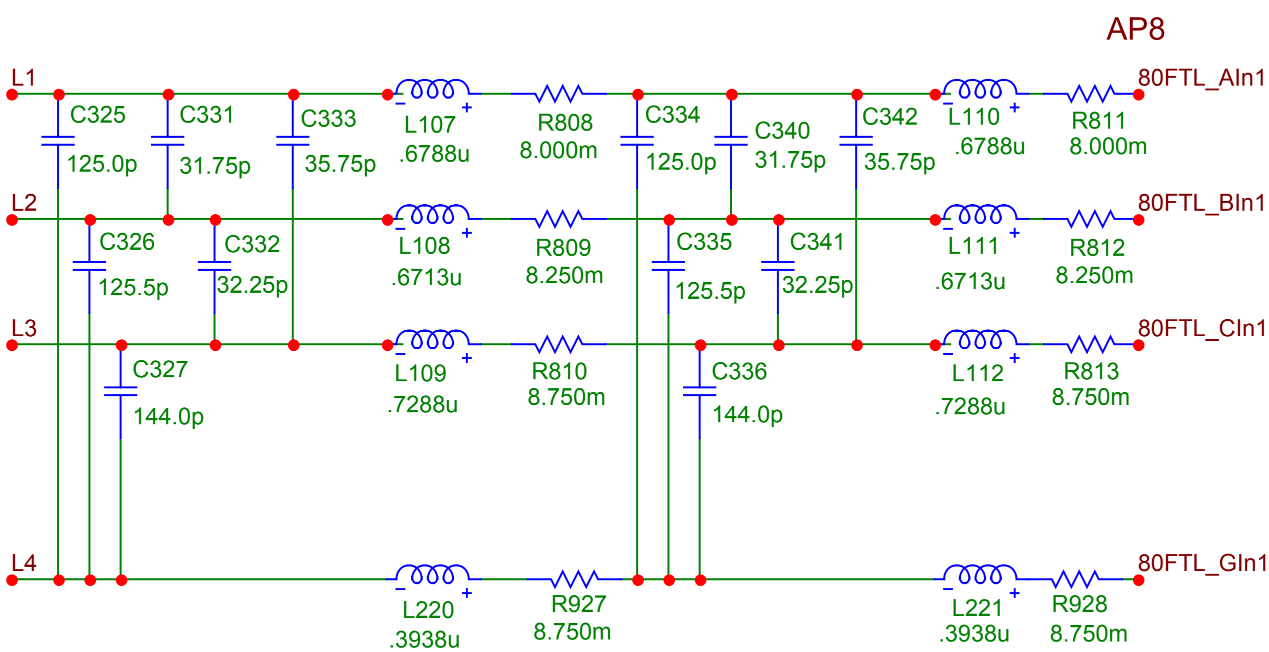


Figure 42. Electric Circuit Schematic of the Last Two Sections of TL11

The connections to the first two sections of TL11 are shown at the left. The connections to TL12 are shown at the right.

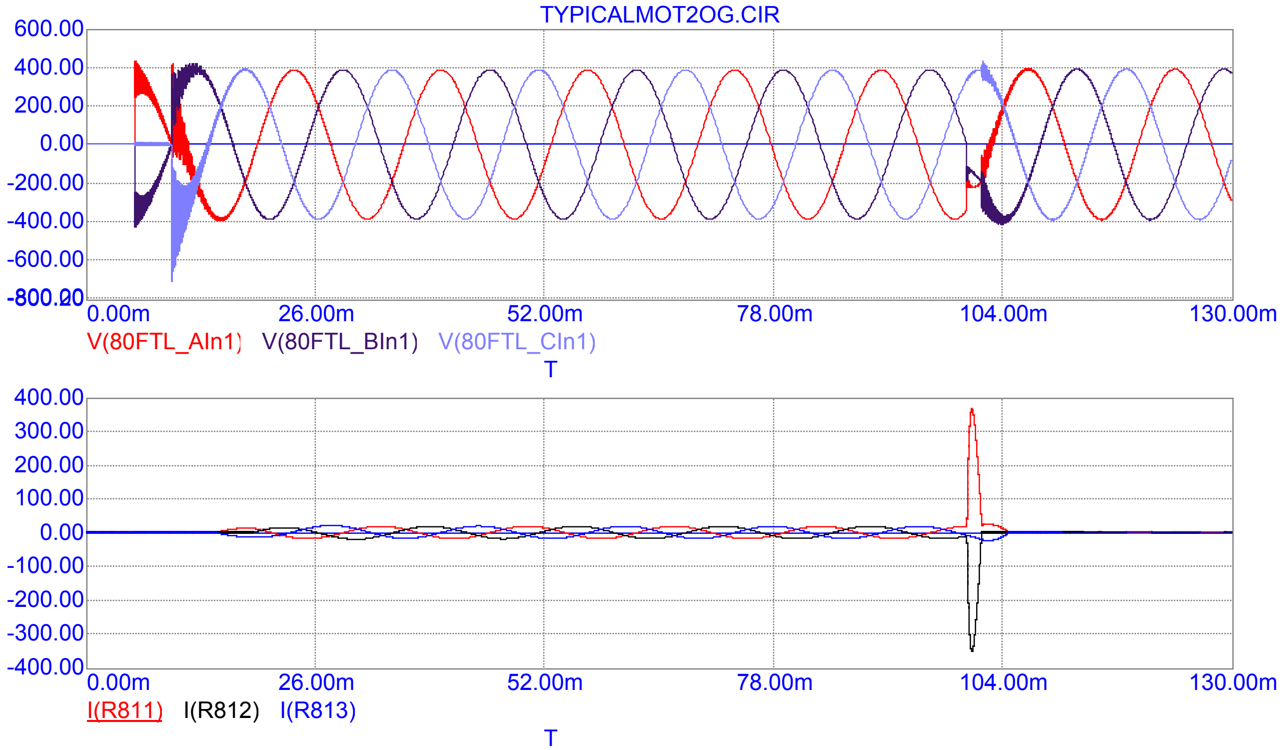


Figure 43. Phase Voltages and Currents at the Output of TL11

The input terminals of TL12 connect to the output terminals of TL11 at Attachment Point 8, which is labeled on the circuit schematic as “AP8.” The electric circuit schematic of TL12 is shown in Fig. 44 and Fig. 45. The input terminals for TL12 are labeled as “80FTL_XIn1,” where X = A, B, C, or G. This model represents an 80-foot-long, four-wire transmission line of the same construction as the eleventh transmission line. This model has the full set of four-wire T-section components. At the output side of this model, the ground line connects to a ground symbol, and the three phase lines connect to three series switch resistors – RCB1A, RCB1B, and RCB1C, which simulate a three-phase circuit breaker. The last symbol in the names of these switch resistors denotes the phase line it is in. The output plane from the twelfth transmission model is labeled “P” on the circuit schematic. The outputs from the three switch resistors connect to the unlabelled input terminals of the 10-hp motor model at the right side of the circuit diagram. The three switch resistors disconnect the 10-hp motor model from TL12 at 101.69 and 104.77 msec into the simulation. The time of disconnection can be changed by setting the values of “101.69M” and “104.77M” to new values in the resistor models. Each of the switch resistors has a resistance of 1.5 mOhm until the phase opening times of 101.69 and 104.77 msec into the simulation when the resistance rapidly transitions smoothly to 1 Gohm, opening and producing an open circuit. The phase voltage and current waveforms at the output from TL12 are shown in Fig. 46. The A phase voltage is V(65), the B phase voltage is V(66), and the C phase voltage is V(67). The A phase current is I(RCB1A), the B phase current is I(RCB1B), and the C phase current is I(RCB1C).

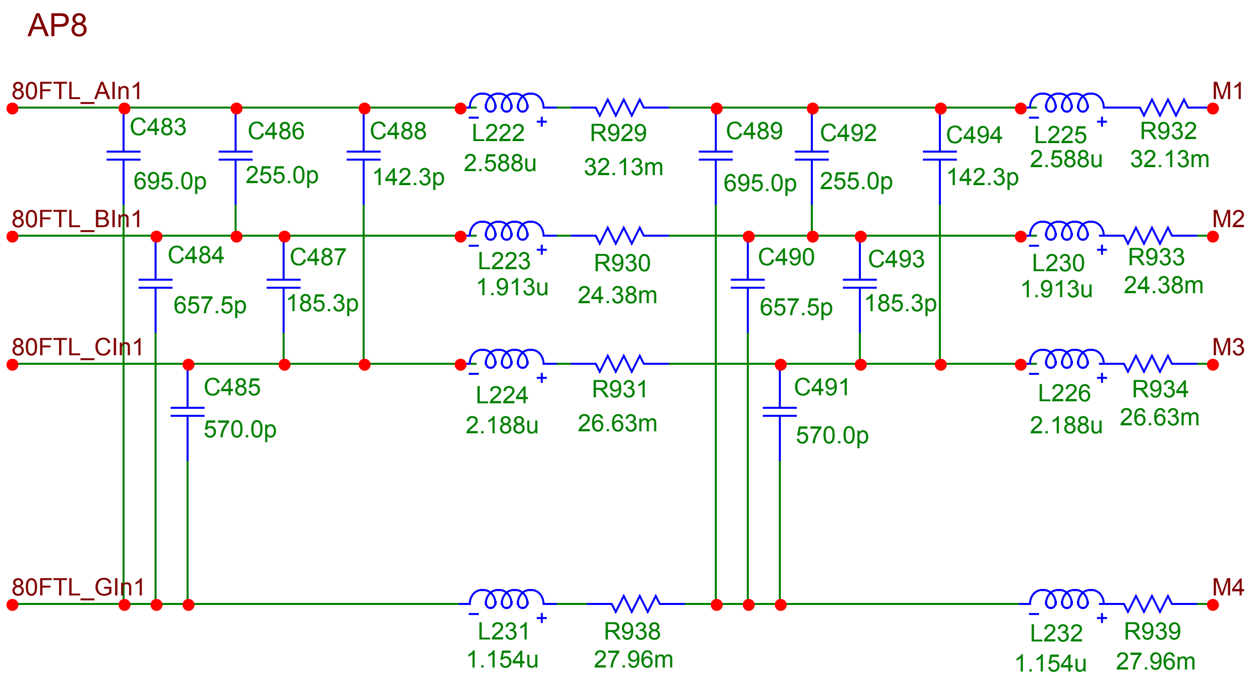


Figure 44. Electric Circuit Schematic of the First Two Sections of TL12

The connections to TL11 are shown at the left. The connections to the last two sections of TL12 are shown at the right.

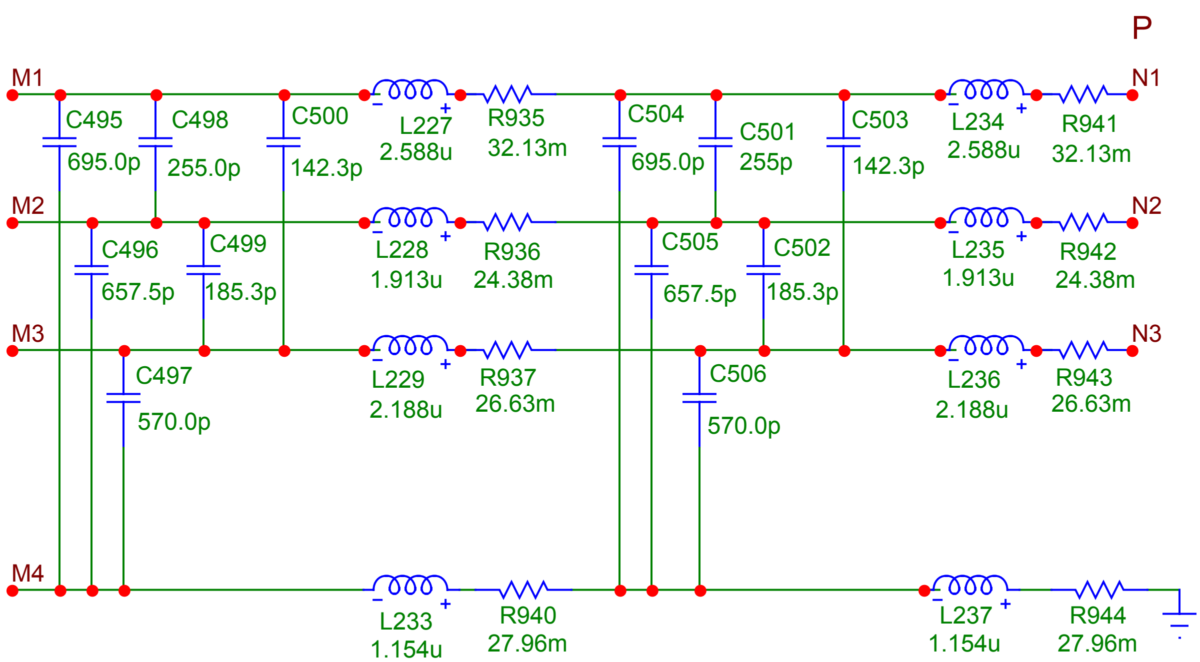


Figure 45. Electric Circuit Schematic of the Last Two Sections of TL12

The connections to the first two sections of TL12 are shown at the left. The connections to the switch resistors, RCB1A, RCB1B, and RCB1C, are shown at the right.

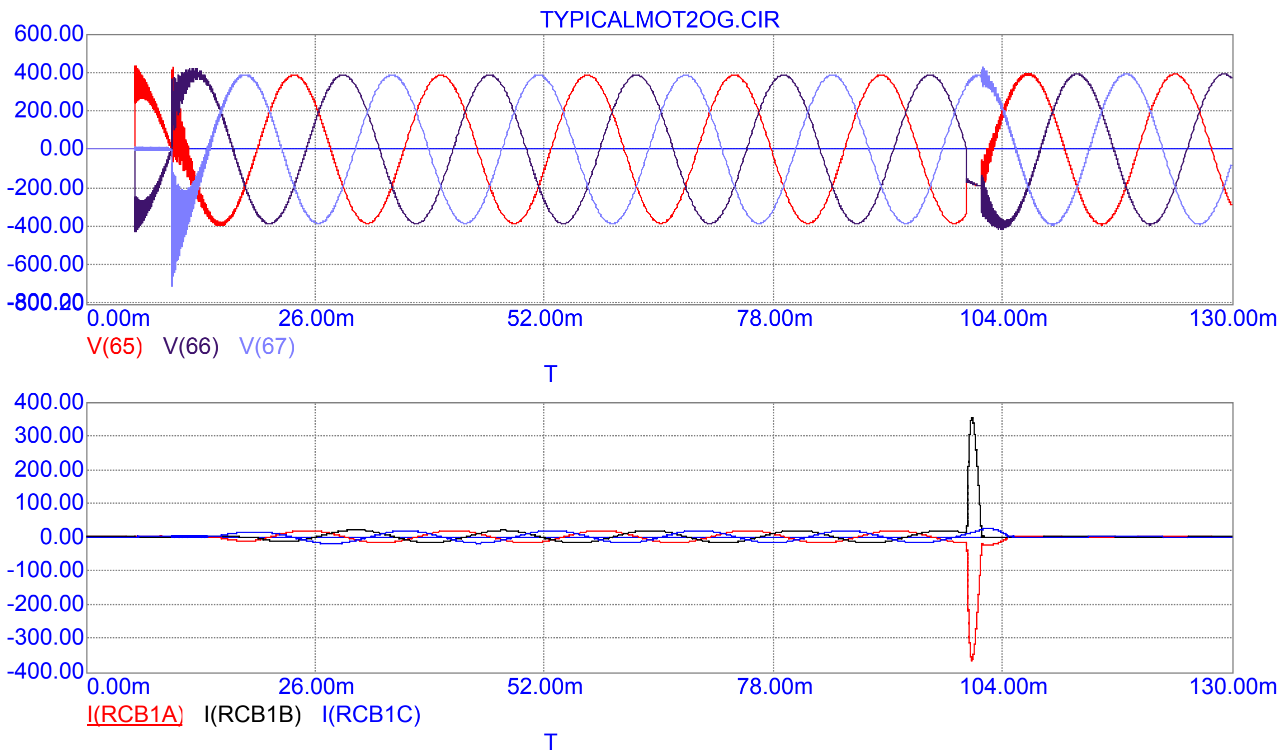


Figure 46. Phase Voltages and Currents at the Output from TL12

The 200 A Distribution Panel Model

The 200 A distribution panel model, shown schematically in Fig. 13, consists of RLC components connected between five conducting lines. These lines represent three phase lines, a neutral line, and a ground line. Two series inductors are in each phase line. Three sets of phase-to-phase shunt capacitances are present, as well as a set of phase-to-neutral shunt capacitances and a set of phase-to-ground shunt capacitances. The component values are from measurements by Michael J. Wilson.[3] The input terminals to the distribution panel are labeled "200ADP_XIn," and the output terminals are labeled "200ADP_XOut," where X = A, B, C, N, or G.

The 100 A Distribution Panel Model

The 100 A distribution panel model, shown schematically in Fig. 25, also has five conducting lines – three phase lines, a neutral line, and a ground line. It also has two series inductances in each phase line, three sets of phase-to-phase shunt capacitances, a set of phase-to-neutral shunt capacitances and a set of phase-to-ground shunt capacitances. It also has two sets of output terminals – a five-line set and a four-line set. The five-line set of output terminals, at the top, is labeled "100ADP_X20Out," where X = A, B, C, N, or G. The four-line set of output terminals, at the bottom, is labeled "100ADP_X60Out," where X = A, B, C, or G. The four-line output terminals follow an LC output section, which consists of three series phase line inductors followed by three phase-to-phase shunt capacitances. The three phase lines to this lower output section connect to the corresponding main phase lines in front of the second set of series inductances, L4A, L4B, and L4C, in the main phase lines. The component values for this model are also obtained from measurements by Michael J. Wilson [3].

The 10-HP Motor Model

In addition to the three circuit breaker switch resistors previously mentioned, the motor model includes three phase-to-phase, zero-value current sources, IloadAB, IloadBC, and IloadCA, to the right of the switch resistors. The electric circuit schematic of the motor model is shown in Fig. 47 and Fig.48. In each of the phase lines to the right of the current sources, there is a series inductor and a series resistor, which represent the steady-state stator resistance and leakage inductance of each motor phase. Each inductance has a value of 8.85 mH; each resistance has a value of 0.681 Ohms. The A phase components are LLRA and RDCA, the B phase components are LLRB and RDCB, and the C phase components are LLRC and RDCC.

To the right of the steady-state resistors are a set of three-phase line switch resistors – R665, R666, and R676. These resistors switch to the "open" state at 100.1 msec. To the right of the phase line switch resistors are a set of two more switch resistors – R699 in the A phase line and R700 in the B phase line. The A phase switch resistor closes at 14.76 msec and places a sine-wave voltage source, V5, at 344.2-V amplitude and 60 Hz with the phase angle of –67.176 degrees, into the A phase line of the motor. The B phase switch resistor closes at 18.97 msec, placing another sine-wave voltage source, V6, at 344.2-V amplitude and 60 Hz with the phase angle of –187.176 degrees, into the B phase line. A third voltage source, V7, at 344.2-V amplitude and 60 Hz with the phase angle of –307.176 degrees, is always connected to the C phase motor line to the right of the C phase switch resistor, R676. The three voltage sources – V5, V6, and V7 – have their negative terminals connected together to form a three-phase wye-connected voltage source with a floating neutral. This three-phase voltage source generates the steady-state back electromagnetic force of the motor.

Three more switch resistors – R674, R675, and R677 – are connected to the right terminals of the steady-state motor stator resistances – RDCA, RDCB, and RDCC. The switch resistors close at 100 msec and connect the exponentially damped sine-wave voltages sources – V8, V9, and V10 – to the right side of the motor phase lines. The voltage source, V8, in the A phase line, has an amplitude of 344.2 V at 60 Hz with a phase angle of –67.176 degrees. It also has an exponential damping factor of 120/sec and a delay of 100 msec for the damping to begin. The voltage source, V9, in the B phase line, has the same values as V8, except that the phase angle is –187.176 degrees. The third voltage source, V10, in the C phase line, also has the same values as V8, except that the phase angle is –307.176 degrees. V8, V9, and V10 have their negative terminals connected together to form a three-phase, wye-connected voltage source with a floating neutral. These three voltage sources simulate a three-phase motor turn off transient, which damps off over time.

The switch resistor, R1000, at the right side of RCB1A and RCB1B simulates a short-circuit fault between the A and B phase lines at 100 msec. At this time, the motor turn off voltage sources are connected to the right sides of resistors, RDCA, RDCB, and RDCC by R674, R675, and R677. The steady-state voltage sources – V5, V6, and V7 – are then disconnected at 100.1 msec by R665, R666, and R676. At 101.69 msec, the B-phase current through RCB1B goes to zero. RCB1B is programmed to open at this time. At 104.77 msec, the currents through RCB1A and RCB1C go to zero. The resistances of RCB1A and RCB1C go to 1 GOhm at this time, fully disconnecting the motor from the facility circuit.

The voltage waveforms at points O1, O2, and O3 are shown in the top frame of Fig. 49. The voltage at point O1 is designated as "V(7)," the voltage at point O2 is designated as "V(8)," and the voltage at point O3 is designated as "V(9)." The waveforms of the currents through resistors RDCA, RDCB, and RDCC are shown in the bottom frame of Fig. 49. The voltage waveforms at the positive terminals of V5, V6, and V7 are shown in the top frame of Fig. 50. The voltage at positive terminal of V5 is designated as "V(10)," the voltage at positive terminal of V6 is designated as "V(12)," and the voltage at positive terminal of V7 is designated as "V(13)." The waveforms of the currents through resistors R665, R666, and R676 are shown in the bottom frame of Fig. 50. The peak value of I(R665) during the impulse is 1168 A. The peak negative value of I(R676) during the impulse is –1196 A. The currents prior to the current impulses at about 100 msec are shown more clearly in Fig. 51, where the current amplitude scale is set to 30 A. The voltage waveforms at the positive terminals of V8, V9, and V10 are shown in the top frame of Fig. 52. The voltage at positive terminal of V8 is designated as "V(14)," the voltage at positive terminal of V9 is designated as "V(16)," and the voltage at positive terminal of V10 is designated as "V(17)." The waveforms of the currents through resistors R674, R675, and R677 are shown in the bottom frame of Fig. 52. The peak value of the positive-going impulse in I(R677) is about 1205 A. The extreme negative value of the impulse in I(R674) is about –1186 A.

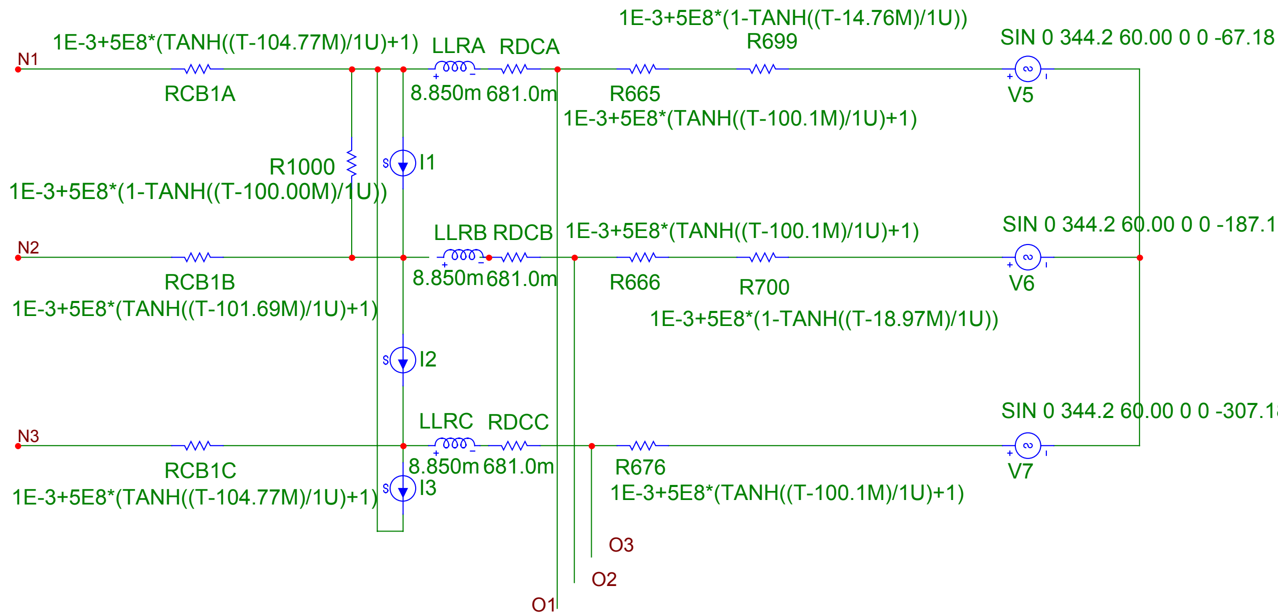


Figure 47. Electric Circuit Schematic of the Upper Branch of the Motor Model

The connections to the output of the twelfth transmission model are shown at the left. The connections to the lower branch of the motor model are shown at the bottom.

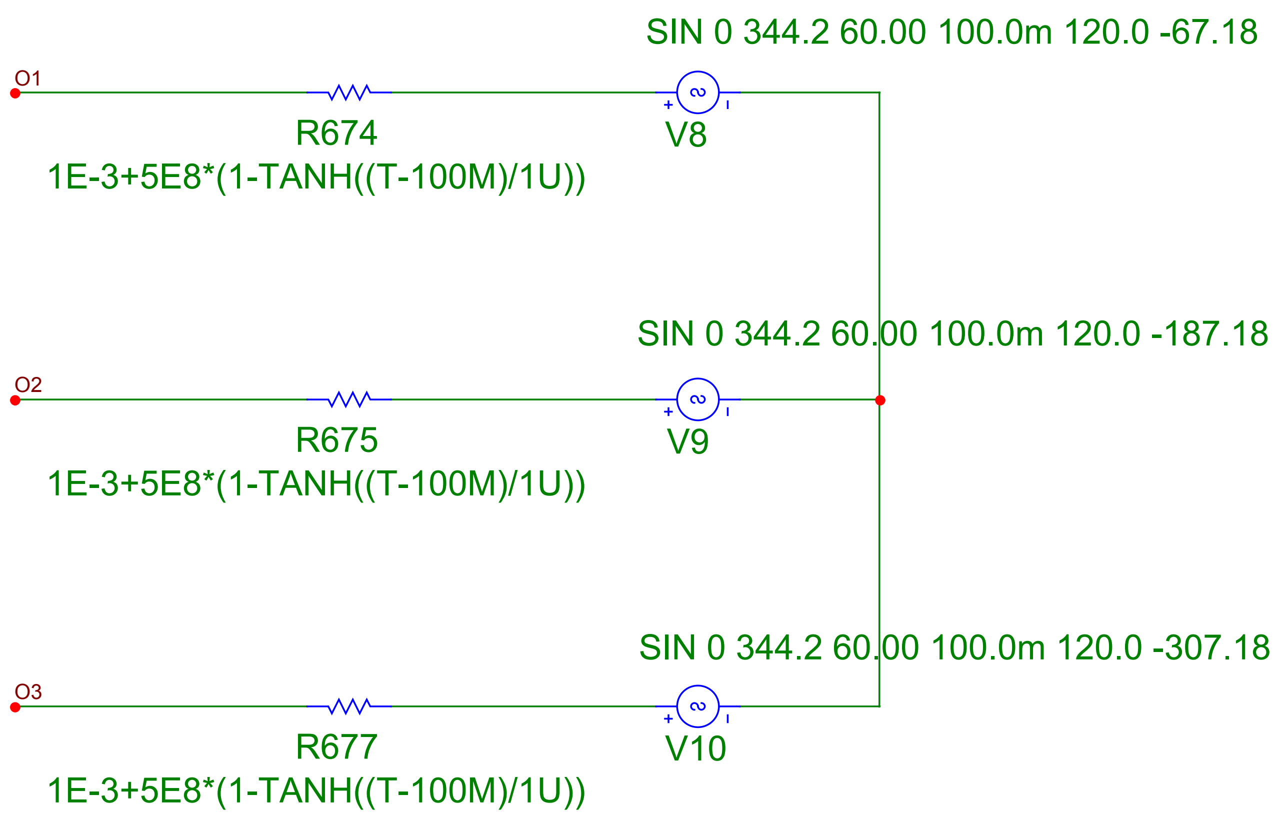


Figure 48 Electric Circuit Schematic of the Lower Branch of the Motor Model

The connections to the upper branch of the motor model are shown at the left.

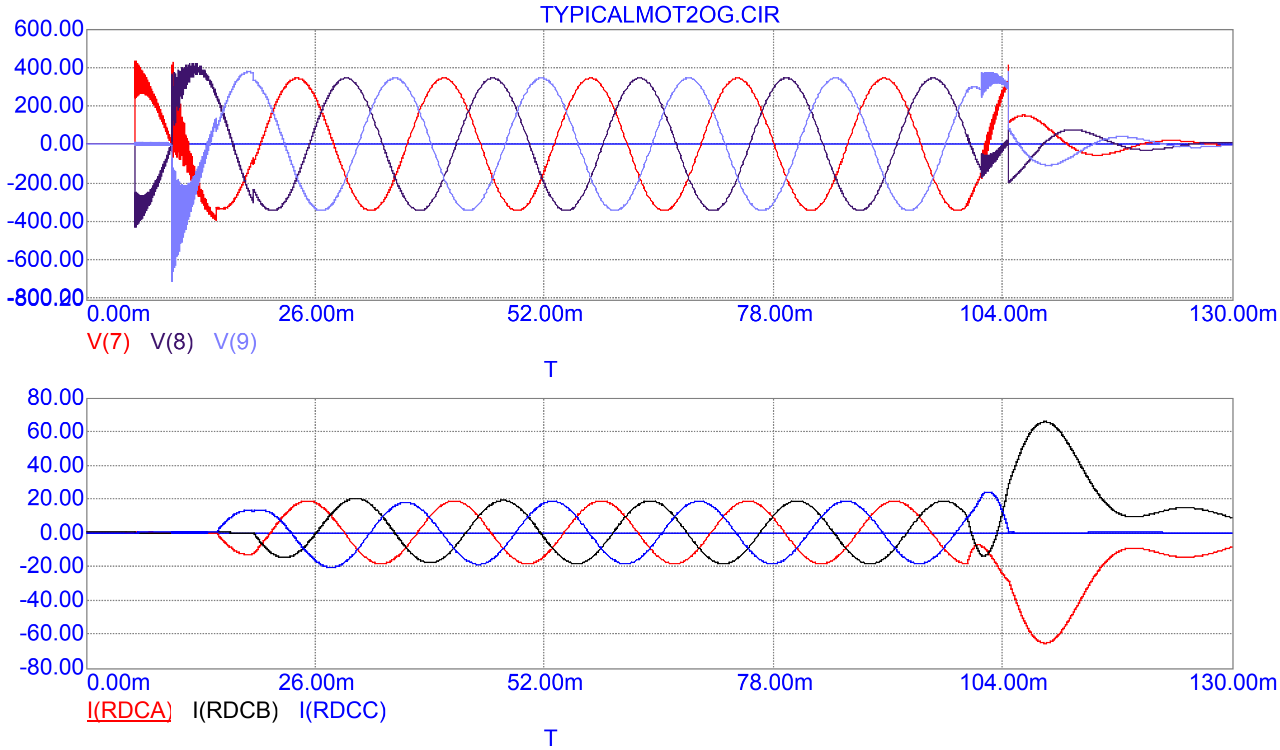


Figure 49. Phase Voltages at Points O1, O2, and O3, and Currents through RDCA, RDCB, and RDCC

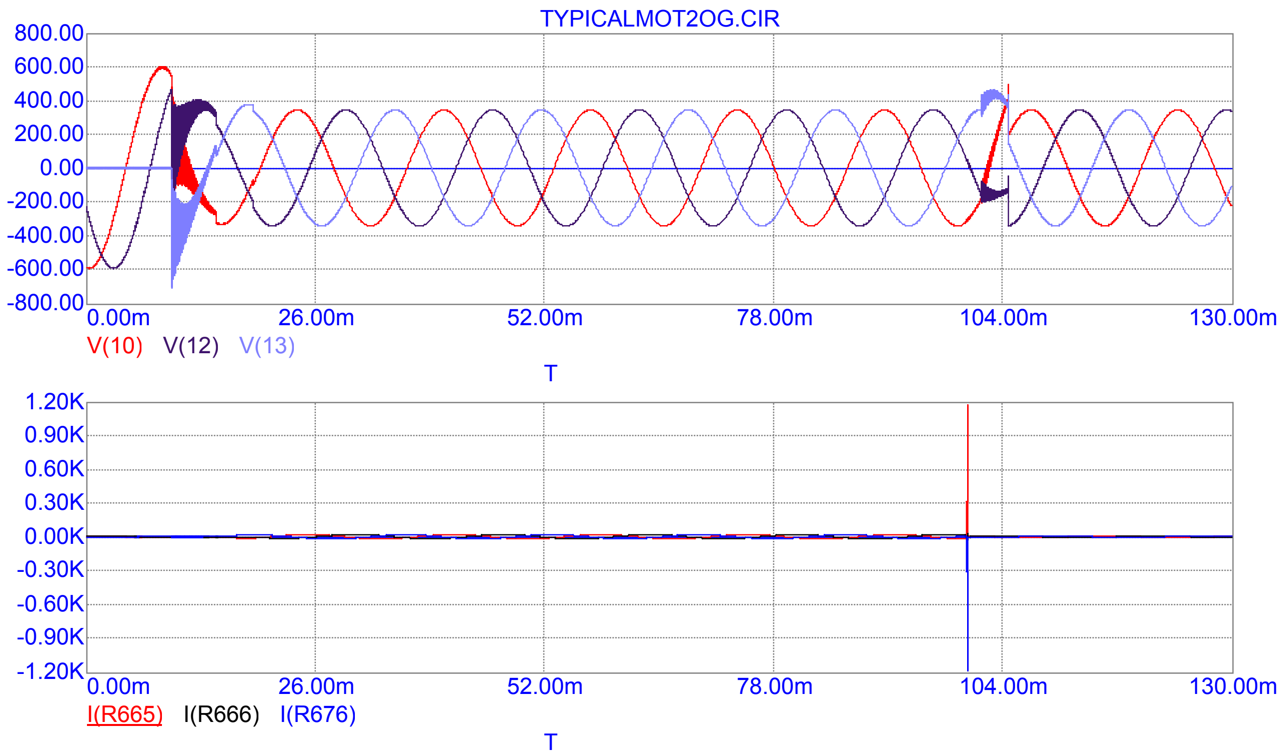


Figure 50. Voltages at the positive terminals of V5, V6, and V7, and Currents through R665, R666, and R676
The voltage at the V5 positive terminal is V(10), the voltage at the V6 positive terminal is V(12), and the voltage at the V7 positive terminal is V(13).

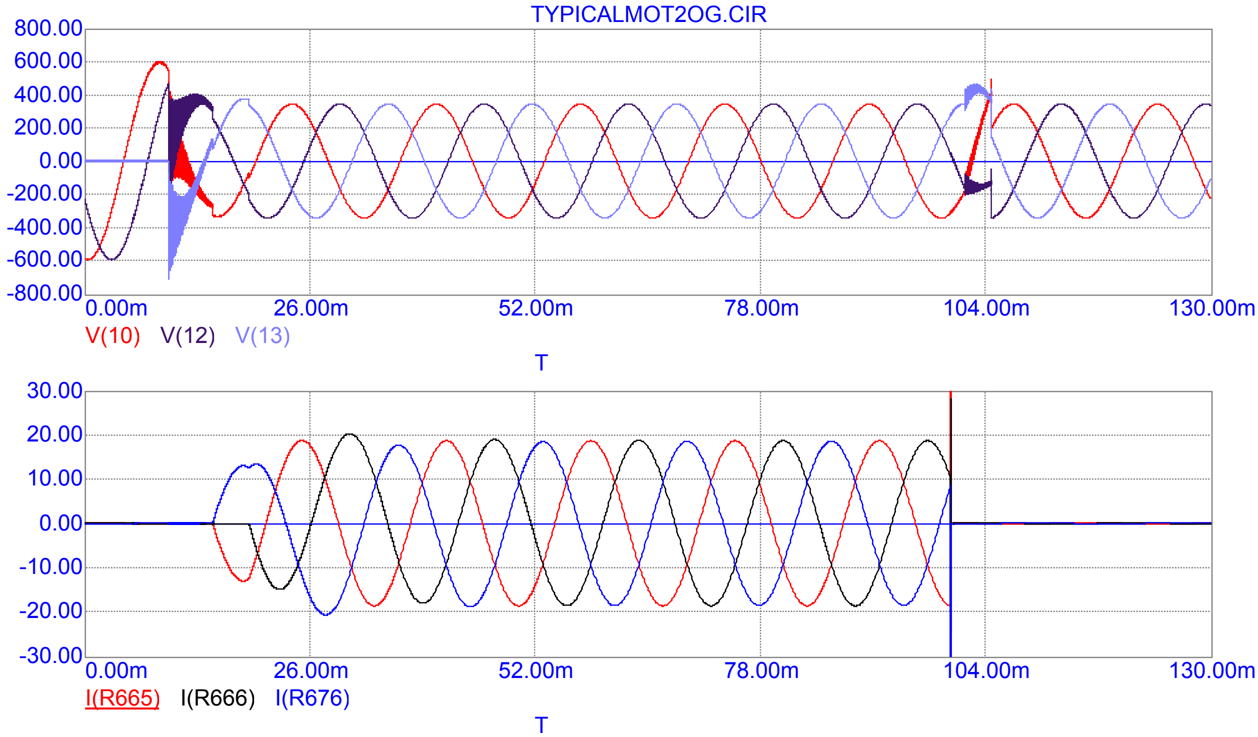


Figure 51. Voltages at the positive terminals of V5, V6, and V7, and Currents through R665, R666, and R676
The voltage at the V5 positive terminal is V(10), the voltage at the V6 positive terminal is V(12), and the voltage at the V7 positive terminal is V(13). The current amplitude scale is limited so that the currents prior to the impulses at ~ 100 msec may be more clearly seen.

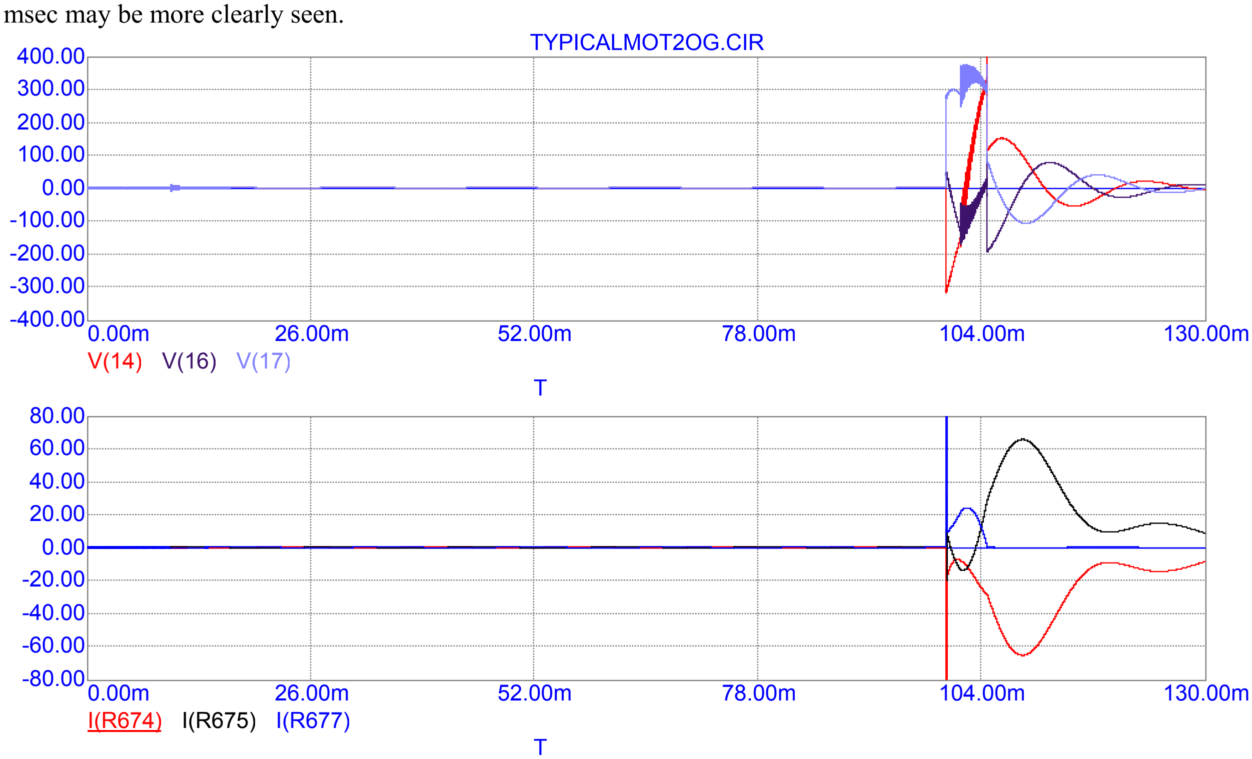


Figure 52. Voltages at the positive terminals of V8, V9, and V10, and Currents through R674, R675, and R677
The voltage at the V8 positive terminal is V(14), the voltage at the V9 positive terminal is V(16), and the voltage at the V10 positive terminal is V(17).

Another circuit schematic contains a startup model for the generic three-phase, 10-hp motor. The electric circuit schematic of this startup motor model is shown in Fig. 53. The previously described back electromagnetic force and startup transient voltage sources are absent, as are the sets of switch resistors to the right of RCB1A, RCB1B, and RCB1C. The three series inductances to the right of the phase-to-phase current sources have values of 5.76 mH. The three series resistances have values of 217 mOhms. The right terminals of the series phase resistances are connected together to form a floating neutral point. The voltages at the series inductor positive terminals for the motor startup model inserted into the circuit at the points N1, N2, and N3 are shown in the top frame in Fig. 54 out to 100 msec. The Voltage at the positive terminal of LLRA, referred to ground, is V(1). The corresponding voltages at the positive terminals of LLRB and LLRC are V(2) and V(3), respectively. The startup motor model is connected in the circuit from t = 0 onward. The currents through RCB1A, RBC1B, and RBC1C are shown in the bottom frame of Fig. 54. Since the currents reach steady values about one cycle after the voltage sources turn on, the amplitude of the motor startup current in this circuit is estimated to be about 191 A.

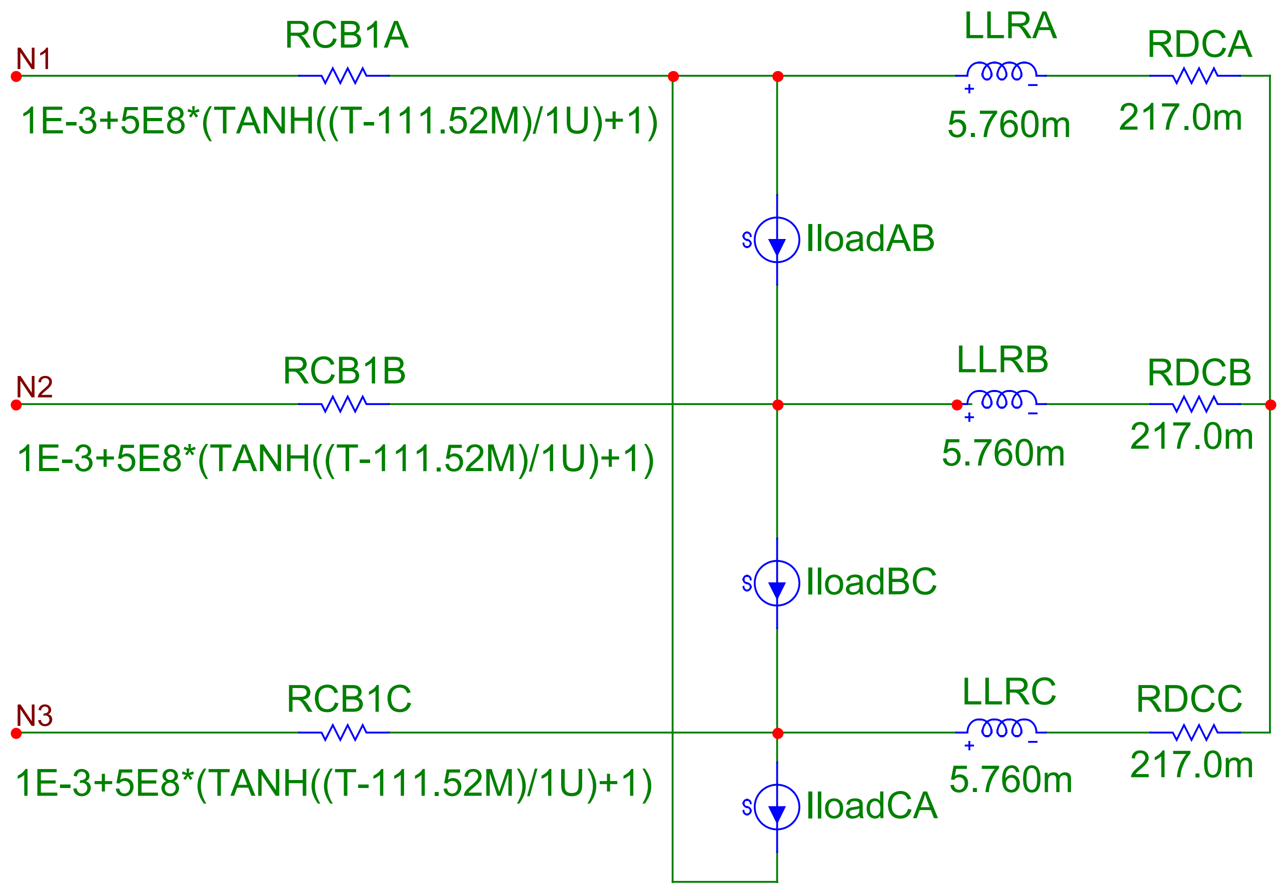


Figure 53. Electric Circuit Schematic of the Startup Motor Model
The switch resistors, RCB1A, RCB1B, and RCB1C, are unchanged from the previous steady-state motor model.

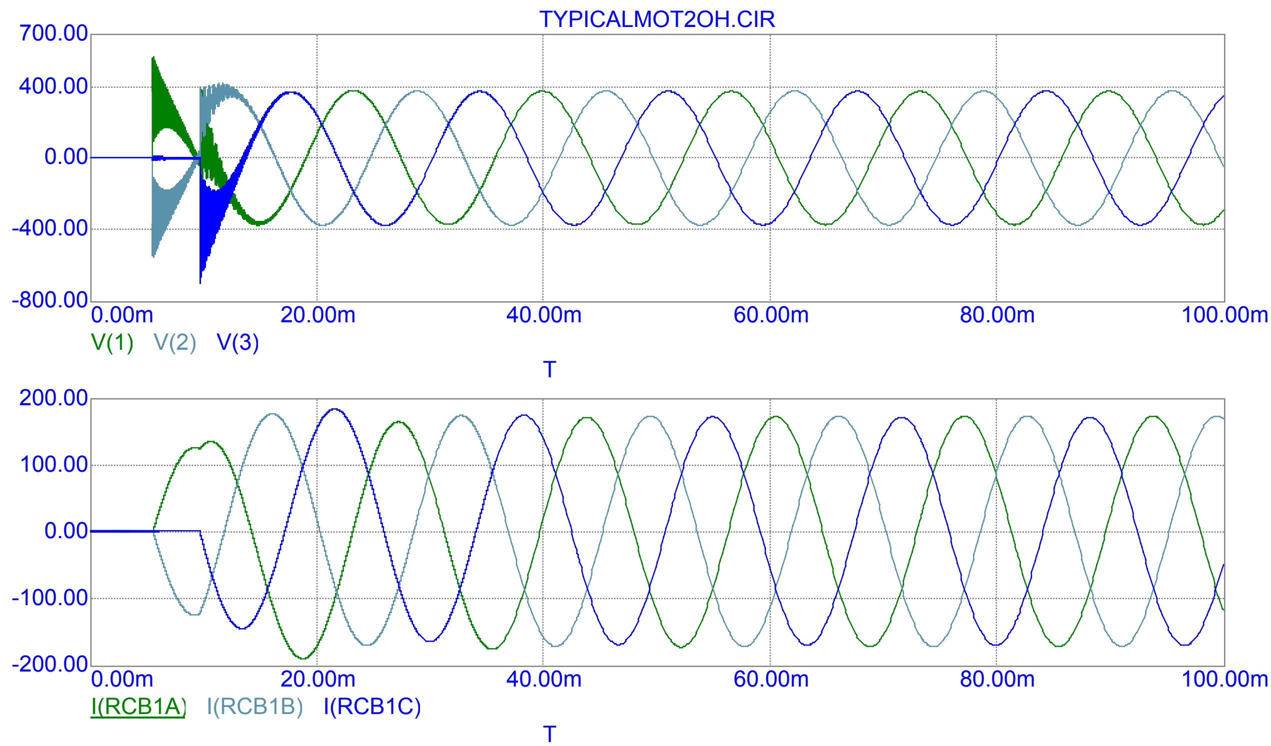


Figure 54. Voltages at the positive terminals of LLRA, LLRB, and LLRC, and Currents through RCB1A, RCB1B, and RCB1C of the Motor Startup Model
The voltage at the LLRA positive terminal is V(1), the voltage at the LLRB positive terminal is V(2), and the voltage at the LLRC positive terminal is V(3).

Summary and Conclusion

The exhaustive level of effort required to model the simulator to the described detail is not required for all interested fault scenarios. For an example a simple DC resistance measurement of a branch circuit is adequate to define the maximum fault current that is possible from an unlimited current source. Only when the related temporal information is required does a more detailed model become necessary. For the purposes of characterizing a general use test bed the level of detail helps identify coupling mechanisms of common branch circuit loads. Additional models of loads, victims, or equipment are presently being developed to insert into the model for specific studies. One of the interesting parameters shown in this effort is the higher than expected impedance (~ 100 Ohm) of the transmission lines in the conduit and distribution panels. Only slight iterations to the model are expected to keep it current and viable as a facility resource tool.

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