Database Modeling for Studies in Power Distribution Systems

Modelado de Base de Datos para Estudios en Sistemas de Distribución de Energía

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ABSTRACT

In most power system analysis studies, databases are stored in IEEE common data format. Although convenient for data exchange between different softwares, this format is not easy to manage in studies of large systems if a user-friendly interface is not available. It also leads to difficulties in recovering data in long-term studies of system performance and power quality. In this paper, a database structure based on tables is proposed. The proposed database is written in Microsoft Office Access and managed through structured query language using MATLAB. The developed database is useful for storing the elements of a power distribution system for power flow and harmonic studies, as well as for providing data for long-term studies and reports.

Keywords: database modeling, power distribution systems, power flow studies, structured query language.

RESUMEN

En la mayoría de los estudios de análisis en sistemas de energía, las bases de datos se almacenan en el formato de datos común IEEE. Aunque conveniente para el intercambio de datos entre diferentes softwares, este formato no es fácil de manejar en estudios de grandes sistemas si un interfaz fácil de usar no está disponible. También resulta en dificultades en la recuperación de datos en estudios a largo plazo del rendimiento del sistema y de calidad de energía. En este trabajo, se propone una estructura de base de datos basada en tablas. La base de datos propuesta está escrita en Microsoft Office Access y gestionada a través del lenguaje de consulta estructurada utilizando MATLAB. La base de datos desarrollada es útil para almacenar los elementos de un sistema de distribución de energía para estudios de flujo de potencia y de armónicos, así como para proporcionar datos para estudios a largo plazo e informes.

Palabras clave: base de datos, estudios de flujo de potencia, sistemas de distribución de energía, lenguaje de consulta estructurada.

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Introduction

Studies of power distribution systems have been developed for decades. Examples include voltage drop investigations (Kersting, 2012; Kagan, 2010) and harmonics analysis (Arrillaga, 2003). In many cases, due to the system complexity and length a significant amount of memory and storage data is required for performing a full analysis. Although professional packages are available and used worldwide (Rizy, 2002), these are neither freely-distributed nor open-source programs. They also experience difficulties when dealing with long-term studies of system performance and power quality, where data storage is necessary for comparisons between different scenarios or to demonstrate the system behavior along a period of time. In addition, data storage in IEEE common data format should present management difficulties in the development of new software, since it consists of a text file format that makes the direct access to specific information less straightforward. This context justifies the continuous development of computer programs and other types of database to support research in power distribution systems (IEEE, 2014).

In this paper, we propose a database structure that can be easily accessed for reading, writing and managing power system data. This database structure is also used for storing results of simple and advanced studies in power systems. This database is based on an open source code that can be easily changed to incorporate new features. It is now used as a support tool for studies of loadability and harmonics in power distribution systems, which are subjects currently investigated by the authors.

This paper is organized as follows. Section "Power Distribution System Models" briefly describes the modeling of the system elements, such as loads, lines and transformers. Section "Database and Structured Query Language" discusses database requirements and data management using structured query lan-

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guage (SQL) in MATLAB. The interface between MATLAB and Microsoft Office Access is described in section "Database Model". Section "Application and Analysis" presents tests that were made using the 4-bus IEEE Distribution Test Feeder to investigate the behavior and functionality of the interface. Conclusions are presented in the last section.

Power Distribution System Models

Traditional radial power distribution systems have one path for power flow from source to costumers. A typical system consists of one distribution substation comprising one or more feeders. Elements of the system are the primary and secondary lines, which are typically three-phase, two-phase or single-phase, the transformers, and the three-phase, two-phase and single-phase loads.

Models of the system elements

Loads: The loads are essentially unbalanced in power distribution systems. In most cases they are modeled assuming constant power, constant current, constant impedance or any combination of these (Kersting, 2012). These models need data like in (1), where rated voltages (V_{an}, V_{bn} and V_{cn}) and apparent powers (S_a, S_b, and S_c) for each phase of the load are required. However, more data is required for models that take into account load response to voltage and frequency (IEEE, 2014) and temporal variations. A database based on tables can easily hold data for load models with these characteristics.

$$\begin{bmatrix} Z_a \\ Z_b \\ Z_c \end{bmatrix} = \begin{bmatrix} \frac{|V_{an}|^2}{S_a^*} & \frac{|V_{bn}|^2}{S_b^*} & \frac{|V_{cn}|^2}{S_c^*} \end{bmatrix}^t \qquad (1)$$

Lines: The model for overhead and underground lines in power distribution systems includes series impedances, shunt admittances and earth effects. For representing the earth return impedance, Carson's equations are used in the approximate form proposed by Kersting (2011), which is presented in (2)-(4). Additional details for obtaining the ABcd parameters of the lines are found in (Kersting, 2012). For harmonic studies, each frequency will lead to a line model that could be stored in a properly modeled database.

$$\hat{z}_{ii} = r_i + 4\omega P_{ii} G + j\left(X_i + 2\omega G \cdot ln\frac{S_{ii}}{R_i} + 4\omega Q_{ii} G\right) \qquad (2)$$

$$X_i = 2\omega G \cdot \ln\frac{R_i}{GMR_i} \qquad (3)$$

$$\hat{z}_{ij} = 4\omega P_{ij} G + j\left(2\omega G \cdot ln\frac{S_{ij}}{D_{ij}} + 4\omega Q_{ij} G\right) \qquad (4)$$

where

$\hat{z}_{ii}$ = self-impedance of conductor i, in Ω/mi;
r_i = resistance of conductor i, in Ω/mi;
ω = system angular frequency, in rad/s;
G = 0.1609344×10^{-3} Ω/mi;
R_i = radius of conductor i, in ft;
GMR_i = geometric mean radius of conductor i, in ft;
$\hat{z}_{ij}$ = mutual impedance between conductors i and j, in Ω/mi;

$$P_{ij} = \frac{\pi}{8} - \frac{1}{3\sqrt{2}} k_{ij} \cos(\theta_{ij}) + \frac{k_{ij}^2}{16} \cos(2\theta_{ij}) \cdot \left(0.6728 + ln\frac{2}{k_{ij}}\right)$$

S_{ij} = distance between conductor i and image j, in ft;

$$Q_{ii} = -0.0386 + \frac{1}{2} ln\frac{2}{k_{ij}} + \frac{1}{3\sqrt{2}} \cos(\theta_{ij})$$

D_{ij} = distance between conductors i and j, in ft;

$$k_{ij} = 8.565 \times 10^{-4} \cdot S_{ij} \cdot \sqrt{\frac{f}{\rho}}$$

θ_{ij} = angle between a pair of lines drawn from conductor i to its own image and to the image of conductor j;
f = system frequency, in Hz;
ρ = earth resistivity, in Ωm.

Transformers: models include three-phase and single-phase transformers. In (Short, 2014) there is an extensive study about distribution transformers and their loading. Kersting (2012) shows a variety of models that can be implemented in computers for power flow studies. The widely used three-phase distribution transformer, connected delta-grounded wye step-down, is modeled through ABdc parameter matrices. In (5)-(8), these matrices are shown for a fundamental frequency application. Equation (7) was developed by the authors including the no-load current and the no-load losses, which are not considered in (Kersting, 2012).

$$[A_t] = \frac{V_{an}}{V_{AB}} \cdot \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \qquad (5)$$

$$[B_t] = Z_t \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

$$[c_t] = \frac{V_{an}}{V_{AB}} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \cdot Y_t \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

$$[d_t] = \frac{V_{an}}{V_{AB}} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \qquad (8)$$

where

V_{an} = rated phase-neutral voltage at low-voltage side, in kV;

V_{AB} = rated phase-phase voltage at high-voltage side, in kV;

Z_t = transformer short-circuit impedance referenced to the low-voltage side, in Ω;

Y_t = transformer shunt admittance referenced to the high-voltage side, in Ω;

As for loads and lines, a transformer model that includes harmonic effects should require extra data. In this case, an additional number of ABcd parameters matrices would have to be stored in the database.

Power flow method

The ABcd parameter matrices for all system elements can be combined for performing power flow studies in power distribution systems (Kersting, 2012). In this paper, the considered method is the ladder interactive technique, which makes the forward and backward calculation of the system behavior with (9) and (10) including buses between the source and the loads (Kersting, 1976). The results of power flow studies can be stored in a database for further use or for reports. This type of analysis can generate a big amount of data.

$$[V_{abc}]_m = [A] \cdot [V_{abc}]_n - [B] \cdot [I_{abc}]_m \qquad (9)$$

$$[I_{abc}]_n = [c] \cdot [V_{abc}]_m + [d] \cdot [I_{abc}]_m \qquad (10)$$

In the equations above, *n* refers to the backward bus, *m* refers to the forward bus, $[V_{abc}]_n$ refers to phase-neutral voltages at bus *n*, $[V_{abc}]_m$ refers to phase-neutral voltages at bus *m*, $[I_{abc}]_n$ corresponds to line currents leaving bus *n*, and $[I_{abc}]_m$ corresponds to line currents entering bus *m*.

Database and Structured Query Language

Arrillaga (2003) describes a computer implementation for harmonic studies with three base points: graphical user interface, simulation algorithm engine and database handling data structure. Some available power flow tools are able to exchange data through the IEEE common data format (Undrill, 1986), but each tool can have its own database format that generally is not open-source. In particular, the IEEE common data format is not well suited for retrieving or inserting data when a great amount of data, like data from systematic harmonic studies, has to be manipulated without a friendly interface. In addition, the IEEE common data format was proposed mostly for power flow studies in power transmission systems. Finally, most data in (IEEE, 2015) are available in MS Excel format file, i.e., table format.

Data storage in tables is visually more understandable and manageable and many softwares for storing tables that form a database are available. Some of them are the 'Microsoft Office Access', which allows up to 3 GB of database, and the 'Microsoft SQL Server Expresser 2014', freely downloadable, which allows up to 10 GB of database. Other professional softwares are SQLite and MySQL. These type of databases with the Structured Query Language (SQL) became widely used due to their simplicity and easy application (Gawlick, 2004). SQL specifies the desired result and not the way to get there. It has functions that enable users to declare what should be done with the collection of data stored in tables, like SELECT, INSERT or UPDATE. Other functions are also available.

The software MATLAB has a DataBase Toolbox that deals with external database using SQL functions. The SQL functions can be programed in .m files or used through the toolbox. Some SQL functions used in MATLAB are described as follows:

Select: the SELECT function allows retrieving data from a table for use as a variable in a computer program. Expressions (11) and (12) respectively show an SQL expression and its MATLAB representation.

$$\boldsymbol{SELECT\ Diameter\ FROM\ tbl\_OH\_CABLE\ WHERE\ Code\_Cable\ = Iris} \qquad (11)$$

$$\boldsymbol{exec(connection, select\ data1\ from\ table\ where\ column = data2\ )} \qquad (12)$$

Insert: the INSERT function is used by MATLAB to export data into a database. It inserts new data in a table for further use. Expressions (13) and (14) respectively show an SQL expression and its MATLAB representation.

$$\boldsymbol{INSERT\ INTO\ tbl\_CONFIGURATION\ (Frequency)\ VALUE\ (60)} \qquad (13)$$

$$\boldsymbol{insert(connection, tablename, colnames, data)} \qquad (14)$$

Update: the UPDATE function exports data into the database table replacing an existing one. Expressions (15) and (16) respectively show an SQL expression and its MATLAB representation.

$$\boldsymbol{UPDATE\ tbl\_PROJECT\ SET\ Node\_Order = 9\ WHERE\ Code\_Project = IEEE13} \qquad (15)$$

$$\boldsymbol{update(connection, tablename, colnames, data, whereclause)} \qquad (16)$$

Database Model

Othman (2012) proposed a database that stores power distribution system elements. The developed software includes a graphical user interface (GUI) developed in Microsoft.NET and C++, and a database using Microsoft SQL Server. Input data are read using forms or .txt files, which means that the user is not able to draw a system. In (Paucar, 2004), the authors developed an efficient and interactive computer program to meet the goal of being user friendly for studies of both transmission and distribution systems. They used platforms such C++, Java 3D and SQL. The distribution system program calculates the system's monetary value by using geographic information system (GIS) data. However it does not perform electric studies. Momin (2014) and Parikh (2009) integrated their GIS to their distribution system analysis software with SQL. In most other works, there is not a connection between power distribution system data and other databases managed by SQL.

In this paper, the MATLAB and Microsoft Office Access are used. MATLAB was chosen because it is widely used for simulation and new implementations in academic studies. As mentioned before, it is also convenient for its Database Toolbox that works with structured query language (SQL), which allows a relatively simple connection to external databases like the Microsoft Office Access (Gawlick, 2004). In the proposed database model, MATLAB is the front controller illustrated Fig. I, where the user can insert all data about the system and run the analysis. This is a simple GUI developed in MATLAB to allow an easy access to the .m files that manage the database. For example, to insert lines in the system one can use the menu bar "Element>Line" or the push button "Line" instead of typing the function on the MATLAB's screen. Microsoft Office Access stores the data in a background database. With those tools, the developed computational system meets the needs of storing data for power distribution systems as well as results obtained from their analysis. Those data can also be recovered for further studies.

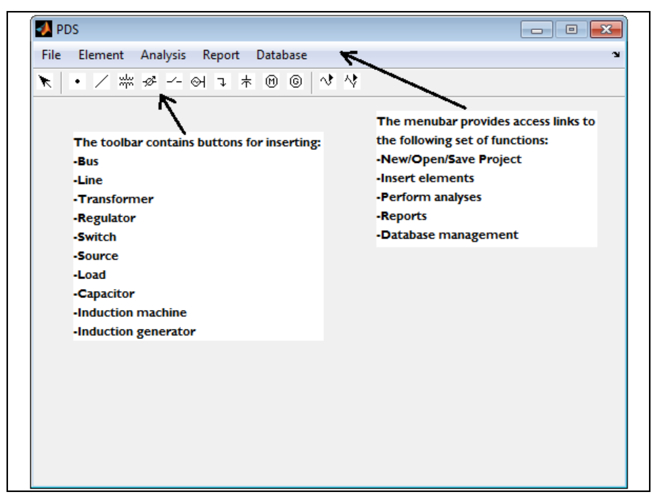

Figure 1. GUI developed at MATLAB to interface with Microsoft Office Access

Fig. 2 shows an overview of the interface between MATLAB and Microsoft Office Access. The elements of the power distribution system are modeled in .m files for MATLAB simulation and a set of analyses can be made such as power flow and loadability studies. Those .m files interact with the Microsoft Office Access database using the SQL functions discussed in the last section.

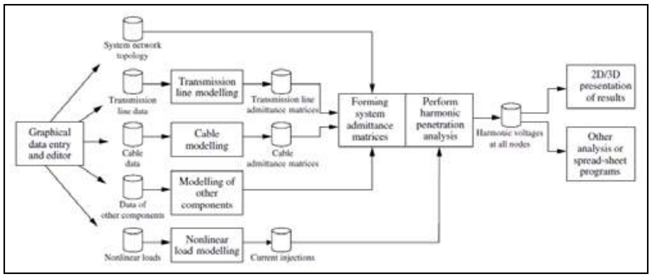

Figure 2. Interface proposed by Arrillaga (2003) for a database

The database model in Microsoft Office Access comprises a set of internal tables. There are two kinds of tables. One is for storing data, such as data for cables, structures, transformers, regulators, and capacitors. Data for overhead cables is stored in a table called *tbl_OH_CABLE*, whose columns are shown in Table I. Data from *tbl_OH_CABLE* table and from *tbl_PHASING* and *tbl_SPACING* tables are used in the procedure that calculates impedance and admittance matrices of overhead lines. The procedure was coded in .m files by using (2)-(4) and SQL functions like SELECT and INSERT. The results from the mentioned procedure are stored in a table named *tbl_CONFIGURATION*, which is illustrated in Fig. 3.

Table 1. Data for overhead cables

Column name	Data type	Description
Internal_code	**Numeric integer long**	**Internal code [automatic increase]**
Code_Cable	**Char string long**	**Standard code cable**
Size	**Char string long**	**Cable's section size [AWG] [MCM]**
Stranding	**Char string long**	**Cable's stranding**
Material	**Char string long**	**Cable's material**
Diameter	**Numeric double**	**Cable's external diameter [in]**
GMR	**Numeric double**	**Cable's Geometric Mean Ratio [ft]**
Resistance	**Numeric double**	**Ohmic resistance at 50ºC [Ω/mi]**
Capacity	**Numeric double**	**Electrical current capacity at 50ºC [A]**

The second kind of table stores data related to the current study, such as data for loads, buses, line parameters and results from power flow studies. For example, the 13-bus IEEE Distribution Test Feeder has 10 different lines with different configuration and length. For harmonic studies, it is needed to model 50 different impedance matrices and another 50 different admittance matrices, corresponding to the fundamental to the fiftieth harmonic order, for each line. Those data, namely ABcd parameter matrices of system elements, are stored in a table called *tbl_ABcd* that is used in power flow studies. Other tables such as *tbl_FLOW* and *tbl_RESULTS* are updated continuously until the current analysis is performed. These tables store, respectively, the power flow direction in the investigated radial power distribution system and the results of the analysis. Table 2 describes data corresponding to results of a given analysis that can be used either in a new analysis or to generate reports.

Table 2. Result data from analysis

Column name	Data type	Description
Code_Project	**Char string long**	**Project's code**
Frequency	**Numeric double**	**System frequency or harmonic order**
Voltage matrix	**Numeric double**	**Matrix of voltage at buses [V] [pu]**
Current matrix	**Numeric double**	**Matrix of line currents [A] [pu]**
Power matrix	**Numeric double**	**Apparent power [kVA], active power [kW], reactive power [kvar]**
Power factor	**Numeric double**	**Matrix of power factor at buses**
Losses	**Numeric double**	**Matrix of lines' losses**
Load	**Numeric double**	**Matrix of loads**

Application and Analysis

The interface between MATLAB and Microsoft Office Access and the storing data procedure was tested using the 4-bus IEEE Distribution Test Feeder. This feeder, shown Fig. 4, consists of an infinite bus that represents the distribution substation; two lines, one with three wires between bus 1 and 2 and the other with four wires between bus 3 and 4; a three-phase distribution transformer connected delta-grounded wye step-down; a balanced load at bus 4.

Two tests were performed. The first one was designed to investigate the use of tables that store data for future analysis. It considered the calculation of the impedance and admittance matrices from the fundamental to fiftieth harmonic order for the 4-wire overhead line shown in Fig. 5. The phase conductor is an ACSR 336.4 MCM 26/7 cable (Linnet) and the neutral conductor is an ACSR 4/0 AWG 6/1 cable (Penguin). The following information was required from the user: system fundamental frequency, earth resistivity, structure code, quantity of phases and neutrals, spacing code, phase conductor type, and neutral conductor type. The procedure ran 50 times in MATLAB, one per harmonic order, in 16.5 seconds including time for access and storage in database. In the fundamental frequency, the calculated impedance and admittance matrices are exactly as in (IEEE, 2015). All results were successfully stored in table *tbl_CONFIGURATION* and, thus, they are available for use in power flow calculations.

tbl_CONFIGURATION

Internal_code	Code_Configuration	Code_Phasing	Code_Cable_Phase	Code_Cable_Neutral	Code_Spacing	Frequency	Resistivity	Zabc	Yabc
297	601	NBAC	Dove	Penguin	500	60	100	[0.3465283977(	[0+i*6.2998079
298	602	NCAB	Penguin	Penguin	500	60	100	[0.7526283977(	[0+i*5.6989848
299	603	NCB	Raven	Raven	505	60	100	[0 0 0;0 1.32941	[0 0 0;0 0+i*4.7
301	604	NAC	Raven	Raven	505	60	100	[1.3237932016;	[0+i*4.6658248
302	605	NC	Raven	Raven	510	60	100	[0 0 0;0 0 0;0 0	[0 0 0;0 0 0;0 0

Figure 3. Rows with impedance and admittance matrices for a frequency of 60 Hz, obtained from table *tbl_CONFIGURATION*, opened at Microsoft Office Access

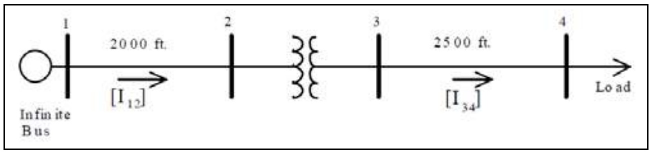

Figure 4. 4-bus IEEE Distribution Test Feeder (IEEE, 2015)

The second test was designed to calculate the 60-Hz power flow in the system of Fig. 4. It tested tables in the database related to those that are updated during the analysis. The user has to enter the following system information using the menu or the buttons illustrated in Fig. 1:

- Project number;
- Bus information: order number, rated voltage;
- Line information: send bus, receiver bus, length, structure;
- Transformer: code;
- Load: bus, type, rated voltage, frequency, powers;
- Source: bus, frequency, rated voltage.

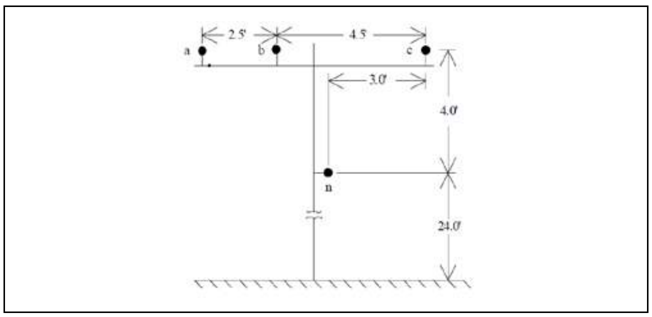

Figure 5. Structure for overhead line with 4 wires (IEEE, 2015)

The power flow routine is a procedure coded in an m. file function. During the forward and backward calculations using (9) and (10), the procedure accesses the database to get the appropriated ABcd matrices between two buses. In the.m. file function, none of variables are stored in the MATLAB workspace and thus the power flow has an additional time delay in its running time. Despite the fact that the connection between MATLAB and the database was satisfactory, the additional simulation time can be a problem in studies dealing with very large systems or in real time simulations. Table 3 shows the results obtained for the 4-bus IEEE Distribution Test Feeder, which are identical to the ones shown in (IEEE, 2015). This indicates a successful integration between MATLAB and Microsoft Office Access, since no data were lost in this task.

Conclusions

This paper demonstrates how a database model using a table format in Microsoft Access can be useful to store the elements of power distribution systems, as well as how the management of this database can be performed with MATLAB using SQL functions. The performance of the link between MATLAB and the database was tested and the results were satisfactory. Further investigations are going to focus on the connection speed between MATLAB and the Access Database, and the necessary changes in the MATLAB code to improve it.

Table 3. Results for 4-bus IEEE Distribution Test Feeder

Data from	Results from 4-bus IEEE Distribution Test Feeder	Results from MATLAB/ Access
Bus 1 [V]	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 7120\angle 0.0° \\ 7120\angle -120.0° \\ 7120\angle 120.0° \end{bmatrix}$	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 7120\angle 0.0° \\ 7120\angle -120.0° \\ 7120\angle 120.0° \end{bmatrix}$
Bus 2 [V]	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 7110\angle -0.3° \\ 7132\angle -120.4° \\ 7124\angle 119.6° \end{bmatrix}$	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 7110\angle -0.3° \\ 7132\angle -120.4° \\ 7124\angle 119.6° \end{bmatrix}$
Bus 3 [V]	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 2249\angle -33.7° \\ 2263\angle -153.4° \\ 2259\angle 86.4° \end{bmatrix}$	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 2249\angle -33.7° \\ 2263\angle -153.4° \\ 2259\angle 86.4° \end{bmatrix}$
Bus 4 [V]	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 1920\angle -39.1° \\ 2054\angle -158.3° \\ 1986\angle 80.9° \end{bmatrix}$	$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 1920\angle -39.1° \\ 2054\angle -158.3° \\ 1986\angle 80.9° \end{bmatrix}$
Line 1-2 [A]	$\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} = \begin{bmatrix} 335.0\angle -35.7° \\ 331.8\angle -154.0° \\ 341.6\angle 85.6° \end{bmatrix}$	$\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} = \begin{bmatrix} 335.0\angle -35.7° \\ 331.8\angle -154.0° \\ 341.6\angle 85.6° \end{bmatrix}$
Line 3-4 [A]	$\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} = \begin{bmatrix} 1041.9\angle -64.9° \\ 973.7\angle 175.9° \\ 1007.0\angle 55.0° \end{bmatrix}$	$\begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix} = \begin{bmatrix} 1041.9\angle -64.9° \\ 973.7\angle 175.9° \\ 1007.0\angle 55.0° \end{bmatrix}$

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