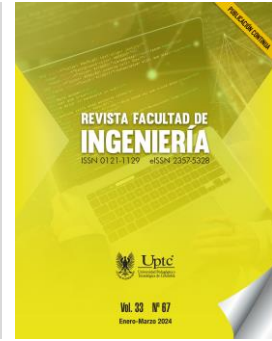


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# Development of an Application for Calculating the Power Flow of Bipolar DC Networks Using the MATLAB Environment

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## Abstract

This work proposes the design of a graphic interface to solve the power flow problem in unbalanced bipolar direct current (DC) networks using the successive approximations method. The goal of the graphic interface is to facilitate the user's calculation of the power flow without the need for prior knowledge of programming languages. This work is divided into three stages. The first presents the mathematical power flow model for unbalanced bipolar DC networks using the successive approximations method. The second presents the implementation of the graphic interface, applying the aforementioned mathematical model. The third stage presents the main characteristics of the DC systems under study, in addition to solving the power flow problem through the program and a comparison with the results reported in the specialized literature. Numerical validations demonstrate that the program solves the power flow and finds the same solution as the specialized literature with 100% efficiency, which confirms the program's accuracy and establishes it as a reliable source of information. This document shows the step-by-step creation of the interface, which was tested with two types of networks to corroborate the validity of the program.

**Keywords:** bipolar direct current networks; power flow application; successive approximations method; unbalanced systems.

## Desarrollo de una aplicación para el cálculo del flujo de potencia en redes DC bipolares utilizando el entorno de MATLAB

### Resumen

Este trabajo plantea el diseño de una interfaz gráfica para resolver el problema de flujo de potencia en redes bipolares de corriente continua (CC) desbalanceadas mediante el método de aproximaciones sucesivas. El objetivo de la interfaz gráfica es facilitarle al usuario el cálculo del flujo de potencia sin la necesidad de conocimientos previos en lenguajes de programación. Este trabajo está dividido en tres etapas. La primera presenta el modelo matemático de flujo de potencia en redes bipolares DC desbalanceadas mediante el método de aproximaciones sucesivas. La segunda presenta la implementación de la interfaz gráfica, aplicando el modelo

matemático mencionado anteriormente. La tercera etapa presenta las principales características de los sistemas DC bajo estudio, además de la solución del problema de flujo de potencia por medio del programa y una comparación con los resultados reportados en la literatura especializada. Las validaciones numéricas demuestran que el programa resuelve el flujo de potencia y encuentra la misma solución de la literatura especializada, con una eficiencia del 100%, lo cual confirma la precisión del programa y lo constituye en una fuente confiable de información. En este documento se muestra el paso a paso de la creación de la interfaz, la cual fue puesta a prueba con dos tipos de redes con el fin de corroborar la validez del programa.

**Palabras clave:** aplicación de flujo de potencia; método de aproximaciones sucesivas; redes bipolares de corriente continua; sistemas desbalanceados.

### **Desenvolvimento de uma aplicação para cálculo de fluxo de potência em redes DC bipolares utilizando o ambiente MATLAB**

#### **Resumo**

Este trabalho propõe o projeto de uma interface gráfica para resolver o problema de fluxo de potência em redes bipolares desequilibradas de corrente contínua (CC) utilizando o método de aproximações sucessivas. O objetivo da interface gráfica é facilitar ao usuário o cálculo do fluxo de potência sem a necessidade de conhecimento prévio de linguagens de programação. Este trabalho está dividido em três etapas. A primeira apresenta o modelo matemático de fluxo de potência em redes DC bipolares desbalanceadas utilizando o método de aproximações sucessivas. A segunda apresenta a implementação da interface gráfica, aplicando o modelo matemático citado acima. A terceira etapa apresenta as principais características dos sistemas CC em estudo, além da solução do problema de fluxo de potência através do programa e uma comparação com os resultados reportados na literatura especializada. As validações numéricas demonstram que o programa resolve o fluxo de potência e encontra a mesma solução na literatura especializada, com eficiência de 100%, o que confirma a precisão do programa e o constitui como uma fonte confiável de informações. Este documento mostra o passo a passo da

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criação da interface, que foi testada com dois tipos de redes para corroborar a validade do programa.

**Palavras-chave:** aplicação de fluxo de potência; método de aproximações sucessivas; redes bipolares de corrente contínua; sistemas desequilibrados.

## I. INTRODUCTION

Electrical distribution systems are responsible for supplying electricity to all residential, commercial, and industrial users at medium- and low-voltage levels [1]. These networks are typically operated with alternating current (AC) and are built with a radial topology in order to simplify protection coordination schemes and reduce investment costs [2].

It is necessary for power systems to have high quality, safety, and efficiency indices. However, the increased demand and environmental constraints, as well as the liberalization of electricity markets, have caused them to operate increasingly close to their stability limits [3]. With the recent advances in power electronics, energy generation systems utilizing non-conventional renewable energy sources, in addition to developing efficient energy storage technologies, are transitioning from passive setups to active networks that interact with the user in an intelligent way [4]. On the other hand, given the development of energy conversion systems, it is currently possible to implement distribution systems that exclusively use direct current (DC) [5] and hybrid schemes that leverage the best traits of AC and DC technologies [6], providing a better performance in terms of energy losses and voltage profiles [7]. This is due to the fact that the concepts of reactive power and frequency are non-existent in these networks [8], which is why their control schemes are easier to design, as their only task is voltage regulation at the DC busbar [9].

In the case of DC operation technologies, distribution networks can be built with two typical topologies. The first is associated with monopolar networks, i.e., those with a positive pole and a neutral return conductor [10]. The second corresponds to DC networks with a bipolar topology, i.e., those with a positive and a negative pole as well as a neutral return conductor [11]. The advantage of a bipolar configuration is that, theoretically, it can transfer twice the power of a monopolar configuration and allows for the connection of loads requiring a voltage level equivalent to twice the power difference between the positive or negative pole and the neutral one [12].

To analyze DC distribution networks with bipolar or monopolar topologies, it is necessary to employ power flow tools, as they allow determining the operating state of a network under steady-state conditions [7]. However, although there are many

reports on the power flow of monopolar networks in the literature [13], those on bipolar networks are scarce, and most focus on analyzing the optimal power flow [14]. Some works on bipolar networks are presented below.

The authors of [11] present a multi-objective optimization methodology for phase balancing in bipolar DC distribution systems. However, they fail to consider the presence of constant-power loads and focus solely on constant impedance and current models, which simplifies the power flow problem and allows obtaining mixed-integer linear programming models.

In [14], the authors analyze the effect of asymmetric loads on network congestion, proposing an optimal power flow to obtain marginal prices per node via an equivalent linear formulation.

The authors of [15] present a recursive optimal power flow for bipolar DC networks with multiple asymmetric loads. The results of the model are validated in systems with 6 and 33 nodes. The proposed mathematical formulation is developed as a function of the current injection method, and the results are compared against simulations of these networks in the PSCAS/EMTDC.

The work by [16] presents a simulation methodology using PSCAD/EMTDC to solve the power flow problem in bipolar networks, for which a three-node test system is employed. However, the authors do not analyze the model's complexity or a convergence test under load variations. They only alter the constant-power terminals for controlled current sources and leave the complications of the solution to a power system analysis tool.

The study by [17] presents the application of a quasi-Newton method for solving the power flow problem in bipolar networks. This method is also known as the Broyden method or the secant, and it ensures a linear convergence to the power flow solution. It is classified as a derivative-free method. The authors validate this methodology in test systems composed of 21, 33, and 85 nodes.

The work by [18] presents a generalized methodology for solving the power flow problem in unbalanced bipolar networks, which is based on applying the Newton-Raphson method. A six-node test system is employed to validate the proposed methodology.

In [19], the authors present a methodology for studying the optimal power flow in bipolar networks, which considers a linear approximation of the power flow equations. Numerical results in test systems with 21 and 85 nodes demonstrate that the linear approximation of the power flow is effective insofar as distributed energy resources are considered in bipolar networks.

Based on the above-presented review of the state of the art regarding power flow for DC networks with a bipolar topology, this article makes the following contributions:

(i) in most cases, calculating voltage values requires solving a system of simultaneous nonlinear equations [20], which is why the successive approximations method is applied for bipolar networks with either a solidly grounded or a floating neutral wire and monopolar and bipolar loads (this is an extension of the method presented by [21]); and (ii) this work presents the development of a graphic interface for implementing the successive approximations method in bipolar distribution networks, as a tool of interest for researchers and students in the electrical sector. This is a novel tool for electrical networks of a bipolar nature. It is important to mention that, in the specialized literature, there is no availability of open-access software for this type of application. This was identified as a research opportunity to which this article seeks to contribute significantly.

The rest of this document is structured as follows. The section titled *Materials and methods* presents the mathematical development of the successive approximations method for bipolar grid applications considering the presence of monopolar and bipolar loads as well as the possibility of having a neutral wire that is either solidly grounded in all nodes or floating. In the *Graphic interface design* section, the main characteristics of the MATLAB application development tool are presented. The section titled *Results and discussion* presents the bipolar configuration of the 21-test feeder used, as well as data on its nodal power consumption and line resistance parameters and the results obtained with the successive approximations method for bipolar networks through its implementation in the developed graphic interface, as well as the corresponding analyses and discussions. Finally, the section titled *Conclusions* describes the main findings of this research, as well as potential research lines.

## II. MATERIALS AND METHODS

This section presents the general methodology regarding the power flow problem for bipolar DC networks, which is based on the successive approximation's method proposed in [22]. In addition, it presents the design of a graphic interface in the MATLAB environment for solving the power flow problem in unbalanced radial or meshed networks.

### A. Power Flow Problem Formulation

In this subsection, matrices will be denoted by capital and italic letters, subscripts will represent nodes, and superscripts will represent iterations.

The power flow problem for bipolar DC networks employs the grid conductance representation [23]. The relationship between voltage and current is considered using the nodal admittance matrix.

$$\begin{bmatrix} I_{g,pn} \\ -I_{d,pn} \end{bmatrix} = \begin{bmatrix} G_{gg,pn} & G_{gd,pn} \\ G_{dg,pn} & G_{dd,pn} \end{bmatrix} \begin{bmatrix} V_{g,pn} \\ V_{d,pn} \end{bmatrix} \quad (1)$$

Where:

$I_{g,pn}$  is the vector containing all currents injected in the positive and negative poles of the slack nodes.

$I_{d,pn}$  is the vector containing all demanded currents in the grid's positive and negative poles.

$G_{pn}$  is the general conductance matrix that relates the slack and demand nodes.

$G_{gg,pn}$  is the component of the matrix  $G_{pn}$  that relates the slack nodes.

$G_{gd,pn}$  is the component of the matrix  $G_{pn}$  that relates the slack and demand nodes.

$G_{dg,pn}$  is the transpose of the matrix  $G_{gd,pn}$ .

$G_{dd,pn}$  is the component of the matrix  $G_{pn}$  that relates the demand nodes.

$V_{g,pn}$  is the vector containing all the voltage outputs of the slack nodes.

$V_{d,pn}$  is the vector containing all the voltages in the demand nodes.

Note that the second row of equation (1) expresses the relationship between the demand currents and the voltage vectors. This implies that the equation is not linear,



as these currents are a function of the demanded voltages and their powers. Therefore, an iterative method is required to solve the power flow problem [5]. To apply the successive approximations method, the second row of equation (1) is reorganized to obtain the voltages of the demand nodes, which was demonstrated in [24] and is shown in equation (2).

$$V_{d,pn} = -G_{dd,pn}^{-1}[G_{dg,pn} V_{s,pn} + I_{d,pn}] \quad (2)$$

The general formula for analyzing the power flow of bipolar DC networks with a solidly grounded neutral wire and unbalanced loads can be obtained by adding an iterative counter to the demand voltage vector based on Tellegen's second theorem [25]. As the demand current vector is a function of the demand voltage vector, the formula for solving the power flow problem is as follows [24]:

$$V_{d,pn}^{t+1} = -G_{dd,pn}^{-1}[G_{dg,pn} V_{s,pn} + I_{d,pn}^t] \quad (3)$$

The iterative process of the successive approximations method ends when the difference between the voltage magnitudes of the current and previous iteration is lower than the pre-established error. This stopping criterion is defined in equation (4).

$$\max \{ |V_{d,pn}^{t+1}| - |V_{d,pn}^t| \} \leq \varepsilon \quad (4)$$

where  $\varepsilon$  is the tolerance error.

One of the great advantages of using equation (3) as an iterative formula is that the inverse of the matrix  $G_{dd,pn}$  must only be calculated once, as it does not change throughout the process [26].

The main difficulty when it comes to solving the power flow problem corresponds to the hyperbolic relationship between voltages and constant power loads [27]. Equations (5) and (6) present the currents of the loads connected between the positive pole and the neutral wire, and those connected between the negative pole and the neutral wire, respectively.

$$I_{dk,p}^t = \frac{P_{dk,p}}{V_{dk,p}^t} \quad (5)$$

$$I_{dk,n}^t = \frac{P_{dk,n}}{V_{dk,n}^t} \quad (6)$$

Where:

$I_{dk,p}^t$  is the current demanded by the positive pole at node k.

$I_{dk,n}^t$  is the current demanded by the negative pole at node k.

$P_{dk,p}$  is the power consumed at node k by the load connected to the positive pole.

$P_{dk,n}$  is the power consumed at node k by the load connected to the negative pole.

$V_{dk,p}^t$  is the voltage level of the positive pole at node k.

$V_{dk,n}^t$  is the voltage level of the negative pole at node k.

Now, if the loads are connected between the positive and negative poles or vice versa, the currents are calculated as follows:

$$I_{dk,p}^t = \frac{P_{dk,pn}}{V_{dk,p}^t - V_{dk,n}^t} \quad (8)$$

$$I_{dk,n}^t = \frac{P_{dk,pn}}{V_{dk,n}^t - V_{dk,p}^t} \quad (9)$$

Where:

$P_{dk,pn}$  is the constant power load connected between the poles.

### **B. Extension to Systems that are not Solidly Grounded**

When designing bipolar DC networks, especially low-voltage ones, there is the possibility that the neutral wire is not connected to the ground in all nodes. The only node that must be grounded is the network supply node [11], implying that the above-presented formulation requires considering said effect in the neutral conductor. To this effect, a new subscript is added to the nomenclature in equation (3), indicating that the neutral wire is not solidly grounded, as shown below:

$$V_{d,p0n}^{t+1} = -G_{dd,p0n}^{-1} [G_{dg,p0n} V_{s,p0n} + I_{d,p0n}^t] \quad (10)$$

Where:

$V_{d,p0n}^{t+1}$  is the vector containing all the voltages of the demand nodes in the following order: positive, neutral, and negative.

$I_{d,p0n}$  is the vector containing all the currents demanded in the positive and negative poles of the grid.

$V_{g,p0n}$  is the vector containing all the voltage outputs of the generators in the following order: positive, neutral, and negative.

$G_{dd,p0n}$  is the component of the conductance matrix that relates the demand nodes, including the conductance of the neutral conductor.

$G_{dg,pn}$  is the component of the conductance matrix that relates the slack and demand nodes, including the conductance of the neutral conductor.

The most significant effect of including this in the power flow problem is related to the demand current. Therefore, if a load is connected between a pole and the neutral conductor, the demand currents are calculated as follows:

$$I_{dk,p}^t = \frac{P_{dk,p0}}{V_{dk,p}^t - V_{dk,o}^t} \quad (11)$$

$$I_{dk,o}^t = \frac{P_{dk,p0}}{V_{dk,o}^t - V_{dk,p}^t} + \frac{P_{dk,no}}{V_{dk,o}^t - V_{dk,n}^t} \quad (12)$$

$$I_{dk,n}^t = \frac{P_{dk,no}}{V_{dk,n}^t - V_{dk,o}^t} \quad (13)$$

Where:

$P_{dk,p0}$  is the constant power load connected between the positive pole and the neutral conductor.

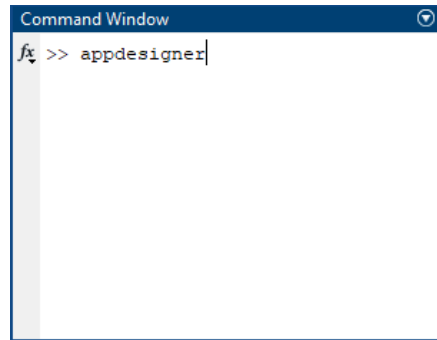
$P_{dk,no}$  is the constant power load connected between the negative pole and the neutral conductor.

$V_{dk,o}^t$  is the voltage of the neutral conductor at node k in iteration t.

### **C. Graphic Interface**

This section presents the implementation of the graphic interface using the mathematical model shown in the previous section. This was done using the MATLAB 2021b software and the application development tool called *AppDesigner*. In the MATLAB environment, to access AppDesigner, the command *appdesigner* must be entered in the command window, as shown in Figure 1.

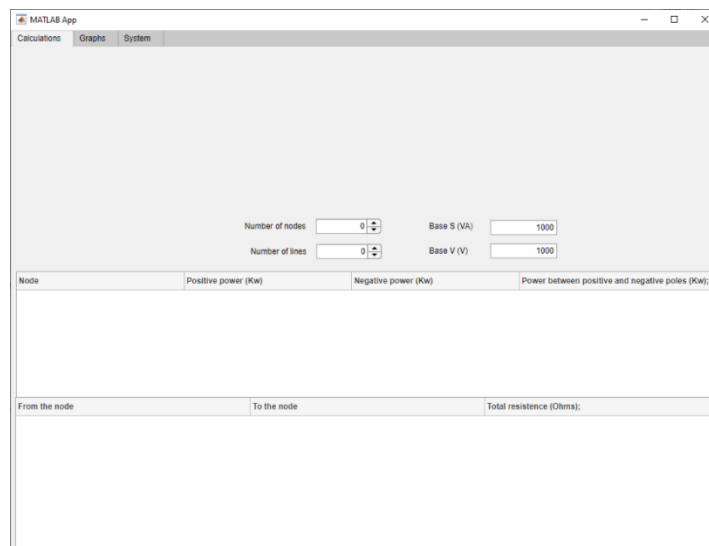
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**Fig. 1.** Opening AppDesigner

Next, the Blank app option is selected, which will open the workspace along with its design and code views, through which the graphic interface and the program code must be adjusted, respectively [28].

The design view is divided into three windows: calculations, graphs, and system. The first of these includes the text editing boxes where the users will enter the program's input data, as shown in Figure 2.



**Fig. 2.** Calculations window (part 1).

For data with multiple inputs, the use of tables is advised, as this facilitates data capture and a better display for the user, which is why this paper uses two tables for entering the load and line data. To facilitate data entry, an option that allows entering information from an Excel file (.xlsx) was added. Two images were added (the logos

of the university), as well as two text boxes, one to name the program and its authors and one to show the results after execution. Finally, a button was added to be pressed when all the input data were ready. Figure 3 shows all the above.

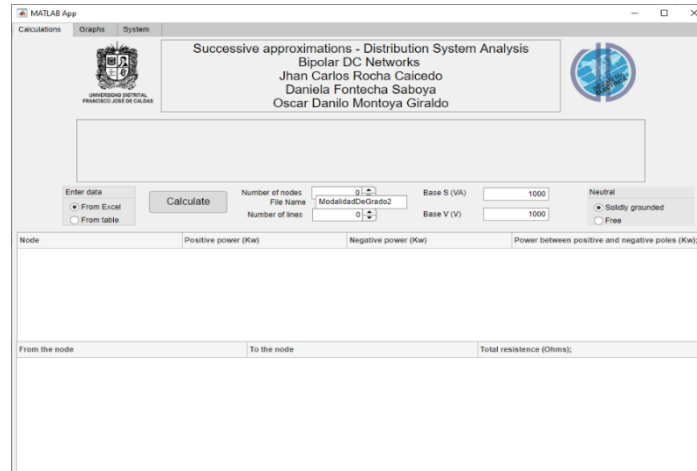


Fig. 3. Calculations window (part 2)

In the graphs window, an axis is added, which allows drawing the entered data on the Cartesian plane, as shown in Figure 4.

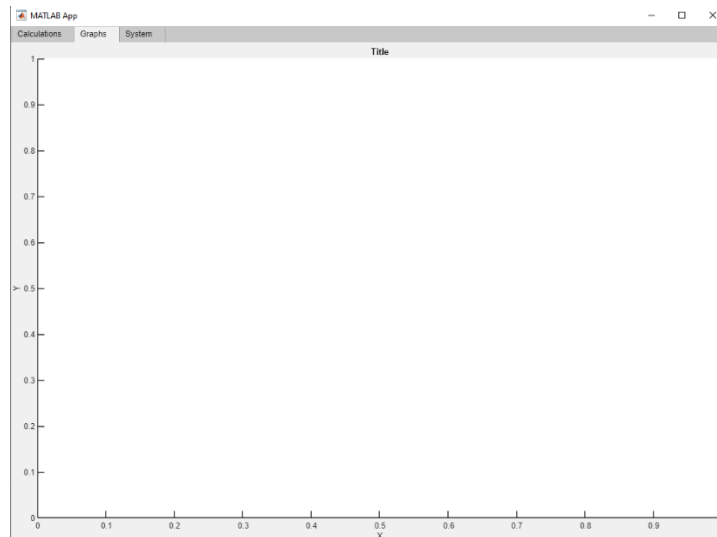


Fig. 4. Graphs window

This window shows the voltage profiles at the end of the program's execution. To the system window, an axis is also added, albeit without a ruler and with a transparent

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background. Thus, this axis does not look like a graph in the Cartesian plane. This window plots an approach to the system's topology using graph theory [29].

It is in the code view that all the entered data are captured. Here, the boxes and tables containing the data are named and stored in global variables for use anywhere in the code and at any time during execution.

When pressing the aforementioned *Calculate* button, the code that calculates the power flow begins its execution. Once this process is complete, the app sends the results obtained to the text area, along with a graph showing the voltage profiles.

After adjusting the functional part of the program, operation details are added in order to make the interface more user-friendly, e.g., the addition of colors for a better look, as shown in Figure 5.

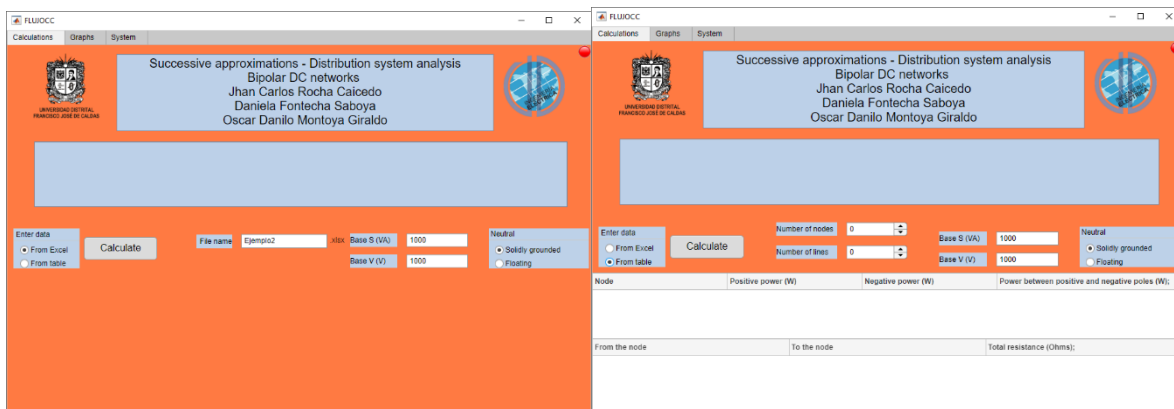


Fig. 5. Final graphic interface

### III. RESULTS AND DISCUSSION

This section presents the test system considered in this work, the numerical validations carried out for its radial and meshed configurations, and an analysis and a discussion of the results obtained.

#### A. Test System

To demonstrate the effectiveness of this proposal and validate the data, a medium-voltage asymmetric bipolar DC distribution network was considered, which is composed of 21 nodes, 22 lines (meshed system), and 21 constant power loads. This feeder was originally used as a balanced network, as presented in [23].

However, in this case, two lines are added, with the configuration shown in Figure 6. Note that, in order to ensure open access to the work presented in this document, the developed tool can be downloaded at [Power flow for bipolar networks](#).

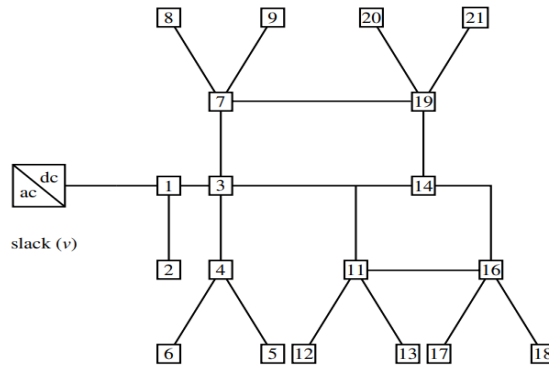


Fig. 6. Nodal connection scheme for the 21-node test feeder.

The 21-node test system's slack node operates at  $\pm 1000V$ . The rest of the electrical parameters can be found in Table 1.

Table 1. Electrical parameters of the 21-node test system.

$Node_i$	$Node_j$	$R_{jk} (\Omega)$	$P_{dk,po} (kW)$	$P_{dk,no} (kW)$	$P_{dk,pn} (kW)$
1	2	0.053	70	100	0
1	3	0.054	0	0	0
3	4	0.054	36	40	120
4	5	0.063	4	0	0
4	6	0.051	36	0	0
3	7	0.037	0	0	0
7	8	0.079	32	50	0
7	9	0.072	80	0	100
3	10	0.053	0	10	0
10	11	0.038	45	30	0
11	12	0.079	68	70	0
11	13	0.078	10	0	75
10	14	0.083	0	0	0
14	15	0.065	22	30	0
15	16	0.064	23	10	0
16	17	0.074	43	0	60
16	18	0.081	34	60	0
14	19	0.078	9	15	0
19	20	0.084	21	10	50
19	21	0.082	21	20	0

For the studied case, two scenarios are evaluated. In the first, the neutral wire is considered to be solidly grounded in all nodes, and in the second, it is considered to be floating.

Two lines are added to the original study case. This information can be found in Table 2. One line goes from node 7 to node 9, and the other one is between nodes 11 and 16 to avoid exceeding a 5% regulation in all nodes. Not surpassing this limit is advisable, which is not possible without these two lines. This will be confirmed in the computational validation.

**Table 2.** Electrical parameters of the additional lines

$Node_i$	$Node_j$	$R_{jk} (\Omega)$
11	16	0.0370
7	19	0.0820

### **B. Numerical validations and discussion**

Considering the above-presented system, the original one was simulated. The results are shown in Table 3. In these numerical results, it can be observed that, in the scenario with the neutral wire grounded in all nodes, some nodes exceed a 10% regulation in the positive pole, specifically nodes 16, 17, and 18. The node with the lowest voltage is no. 17, with a 10.99% regulation. Compared to its counterpart, the negative pole exhibits the lowest voltage at node 18, with a 9.14 regulation. This is due to the fact that the load is unbalanced. The total load reported for the positive pole is 554 kW, while that of the negative pole is 445 kW, which represents a difference of over 100 kW.

**Table 3.** Voltage for the two simulation cases in the original system

Node	Grounded neutral wire			Floating neutral wire		
	Positive pole	Neutral wire	Negative pole	Positive pole	Neutral wire	Negative pole
1	1000	0	-1000	1000	0	-1000
2	996.2761	0	-994.6716	996.2822	-1.6193	-994.6629
3	960.0684	0	-968.4101	959.5206	9.2158	-968.7363
4	952.3714	0	-962.7830	951.7636	11.3722	-963.1359
5	952.1067	0	-962.7830	951.4955	11.6403	-963.1359
6	950.4397	0	-962.7830	949.8031	13.3328	-963.1359
7	953.7448	0	-964.5412	953.1184	11.7701	-964.8885
8	951.0868	0	-960.4285	950.4291	10.3923	-960.8214



Node	Grounded neutral wire			Floating neutral wire		
	Positive pole	Neutral wire	Negative pole	Positive pole	Neutral wire	Negative pole
9	943.8619	0	-960.7609	943.1110	17.9963	-961.1074
10	937.4888	0	-948.4699	936.5747	12.4856	-949.0603
11	930.9221	0	-942.8952	929.9260	13.6205	-943.5464
12	925.1152	0	-936.9933	924.0247	13.7095	-937.7342
13	926.9467	0	-939.7613	925.9357	14.4763	-940.4120
14	916.4716	0	-930.2941	915.1628	15.9905	-931.1533
15	905.4445	0	-921.0086	903.9041	18.1140	-922.0181
16	896.1421	0	-913.9506	894.4081	20.6576	-915.0657
17	890.1027	0	-911.4861	888.2594	24.3408	-912.6002
18	893.0583	0	-908.6017	891.2523	18.5787	-909.8310
19	909.9529	0	-924.3558	908.5513	16.7360	-925.2873
20	905.7062	0	-921.1449	904.2616	17.8323	-922.0939
21	908.0565	0	-922.5782	906.6158	16.9277	-923.5435

In the simulation where the neutral wire is only grounded at the slack node, it is observed that the neutral conductor of nodes 16 and 17 exceeds 20 V in magnitude, which may have negative consequences for the sensitivity of some devices. It should also be emphasized that voltage regulation slightly decreases compared to the previous case, but this is not a significant fact.

To demonstrate the effectiveness of the application for solving the power flow of unbalanced bipolar DC networks, we included a scenario with two additional lines (Table 2), aiming to reduce voltage regulation at critical nodes and use a meshed network to confirm that our approach works with both topologies.

Table 4 shows the results of the new simulation case. Accordingly, it can be stated that the power losses for the solidly grounded scenario is 75.1832 kW, 3.5540 kW less than those of the case with the floating neutral wire. This is associated with the currents flowing through the neutral wire, as a result of load imbalances between the positive and negative poles.

**Table 4.** Voltage for the two simulation cases in the modified system

Node	Grounded neutral wire			Floating neutral wire		
	Positive pole	Neutral wire	Negative pole	Positive pole	Neutral wire	Negative pole
1	1000	0	1000	1000	0	1000
2	996.2761	0.0000	994.6716	996.2822	-1.6193	994.6629
3	960.5554	0.0000	968.7957	960.1064	8.9492	969.0556
4	952.8622	0.0000	963.1711	952.3551	11.1017	963.4568
5	952.5976	0.0000	963.1711	952.0872	11.3696	963.4568
6	950.9314	0.0000	963.1711	950.3963	13.0605	963.4568

Node	Grounded neutral wire			Floating neutral wire		
	Positive pole	Neutral wire	Negative pole	Positive pole	Neutral wire	Negative pole
7	950.2970	0.0000	961.2054	949.7234	11.8017	961.5251
8	947.6292	0.0000	957.0782	947.0243	10.4196	957.4439
9	940.3779	0.0000	957.4115	939.6789	18.0515	957.7304
10	944.0865	0.0000	954.5621	943.4321	11.5340	954.9661
11	934.2946	0.0000	946.4192	933.5170	13.3896	946.9066
12	928.5089	0.0000	940.5396	927.6406	13.4729	941.1135
13	930.3339	0.0000	943.2969	929.5420	14.2418	943.7838
14	939.6834	0.0000	950.9273	938.9764	12.3878	951.3641
15	934.6149	0.0000	946.3633	933.8392	13.0128	946.8520
16	931.1309	0.0000	943.8982	930.3101	14.0995	944.4095
17	925.3137	0.0000	941.5199	924.4222	17.6084	942.0307
18	928.1637	0.0000	938.7210	927.3012	11.9995	939.3007
19	941.6278	0.0000	952.9884	940.9537	12.4401	953.3937
20	937.5209	0.0000	949.8788	936.8176	13.4789	950.2965
21	939.7955	0.0000	951.2644	939.0951	12.5979	951.6930

On the other hand, voltage regulation decreases significantly with respect to the original system, i.e., from 10.99% in the radial network to 7.47% in the meshed one. In the positive pole, the voltage goes from 890.1027 V to 925.313 V. This may be due to the fact that adding lines changed the current distribution, and the most remote nodes do not perceive such a drastic voltage difference.

Figure 7 shows the voltage profiles for the modified study case with the solidly grounded neutral wire, and Figure 8 presents the voltage profile for the modified scenario with the floating neutral conductor.

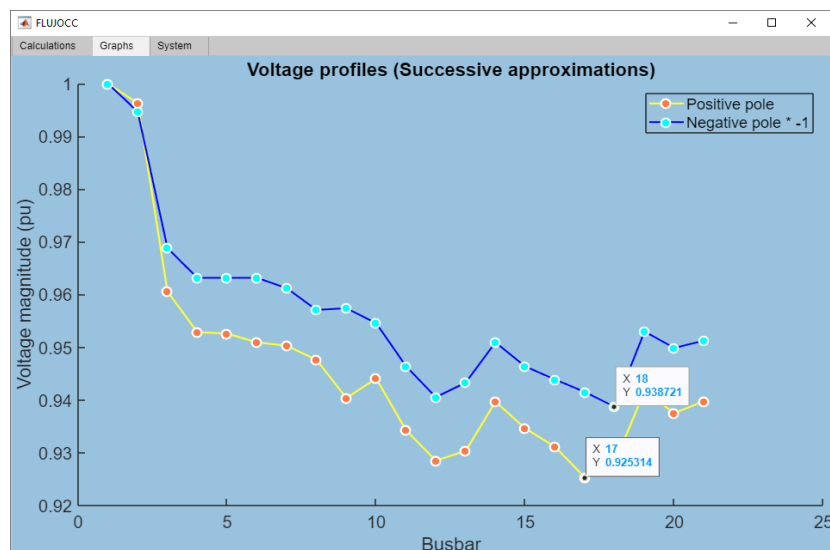


Fig. 7. Voltage profiles for the modified study case (solidly grounded neutral wire).

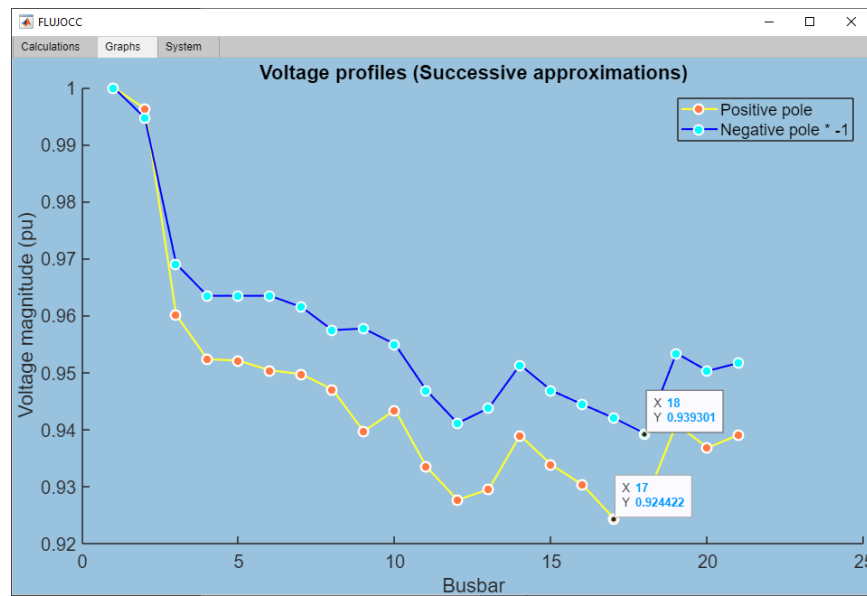


Fig. 8. Voltage profiles for the modified study case (floating neutral wire)

## V. CONCLUSIONS

This work analyzed solidly grounded and non-grounded bipolar DC networks, to which the same successive approximations method was applied, demonstrating its effectiveness in both cases. In addition, this method can be used in both radial and meshed grids. The implementation of a graphic interface facilitates its use; as it is user-friendly, this interface can be used by anyone with basic knowledge of the subject.

A graphical analysis of voltage profiles allows quickly determining key factors in a bipolar DC network, such as the system's electrical center (i.e., the node with the highest voltage), the nodes in which the highest load is concentrated, and, in some cases and with the help of a system topology scheme, the lines with the greatest losses.

As possible research works, the following could be conducted in the future: (i) implementing new power flow methods for bipolar grids based on Taylor approximations and the triangular method; (ii) studying the phase balancing problem by combining the successive approximations method and a metaheuristic algorithm of a binary nature; and (iii) proposing a convex reformulation to study the optimal

power flow problem in bipolar networks with a high penetration of distributed energy resources.

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## **AUTHORS CONTRIBUTION**

**Oscar Danilo Montoya-Giraldo:** conceptualization; methodology; data analysis; writing-review and editing.

**Jhan-Carlos Rocha:** research; methodology; data analysis; software; writing-original draft.

**Daniela Fontecha-Saboya:** research; methodology; data curation; software; writing-original draft.

## **REFERENCES**

- [1] M. I. Muhammad Ridzuan, N. F. Mohd Fauzi, N. N. R. Roslan, N. Mohd Saad, "Urban and rural medium voltage networks reliability assessment," *SN Applied Sciences*, vol. 2, 2020. <https://doi.org/10.1007/s42452-019-1612-z>
- [2] M. Lavorato, J. F. Franco, M. J. Rider, R. Romero, "Imposing Radiality Constraints in Distribution System Optimization Problems," *IEEE Transactions on Power Systems*, vol. 27, pp. 172-180, 2012. <https://doi.org/10.1109/tpwrs.2011.2161349>
- [3] J. A. Melo Rodriguez, C. A. Cortés Guerrero, "Análisis de vulnerabilidad de sistemas de potencia incluyendo incertidumbre en las variables con lógica difusa tipo 2," *Revista Tecnura*, vol. 20, no. 49, pp. 100-119, 2016. <https://doi.org/10.14483/udistrital.jour.tecnura.2016.3.a07>
- [4] P. Siano, G. Rigatos, A. Piccolo, "Active Distribution Networks and Smart Grids: Optimal Allocation of Wind Turbines by Using Hybrid GA and Multi-Period OPF," in *Computational Intelligence Systems in Industrial Engineering*, Atlantis Press, 2012, pp. 579-599. [https://doi.org/10.2991/978-94-91216-77-0\\_27](https://doi.org/10.2991/978-94-91216-77-0_27)
- [5] A. Garces, "Uniqueness of the power flow solutions in low voltage direct current grids," *Electric Power Systems Research*, vol. 151, pp. 149-153, 2017. <https://doi.org/10.1016/j.epsr.2017.05.031>

- [6] L. Z. Lu Zhang, W. T. Wei Tang, J. L. Jun Liang, G. L. Gen Li, Y. C. Yongxiang Cai, T. Y. Tao Yan, "A medium voltage hybrid AC/DC distribution network and its economic evaluation," in *12th IET International Conference on AC and DC Power Transmission*, 2016. <https://doi.org/10.1049/cp.2016.0446>
- [7] L. F. Grisales-Noreña, O. D. Montoya, W. J. Gil-González, A.-J. Perea-Moreno, M.-A. Perea-Moreno, "A Comparative Study on Power Flow Methods for Direct-Current Networks Considering Processing Time and Numerical Convergence Errors," *Electronics*, vol. 9, e2062, 2020. <https://doi.org/10.3390/electronics9122062>
- [8] O. D. Montoya Giraldo, A. Arias-Londoño, A. Molina-Cabrera, "Branch Optimal Power Flow Model for DC Networks with Radial Structure: A Conic Relaxation," *Tecnura*, vol. 26, pp. 30-42, 2022. <https://doi.org/10.14483/22487638.18635>
- [9] W. Gil-González, O. D. Montoya, C. Restrepo, J. C. Hernández, "Sensorless Adaptive Voltage Control for Classical DC-DC Converters Feeding Unknown Loads: A Generalized PI Passivity-Based Approach," *Sensors*, vol. 21, e6367, 2021. <https://doi.org/10.3390/s21196367>
- [10] V. Monteiro, L. F. C. Monteiro, F. L. Franco, R. Mandrioli, M. Ricco, G. Grandi, J. L. Afonso, "The Role of Front-End AC/DC Converters in Hybrid AC/DC Smart Homes: Analysis and Experimental Validation," *Electronics*, vol. 10, e2601, 2021. <https://doi.org/10.3390/electronics10212601>
- [11] B. S. Chew, Y. Xu, Q. Wu, "Voltage Balancing for Bipolar DC Distribution Grids: A Power Flow Based Binary Integer Multi-Objective Optimization Approach," *IEEE Transactions on Power Systems*, vol. 34, pp. 28-39, 2019. <https://doi.org/10.1109/tpwrs.2018.2866817>
- [12] G. Van den Broeck, S. De Breucker, J. Beerten, J. Zwysen, M. Dalla Vecchia, J. Driesen, "Analysis of three-level converters with voltage balancing capability in bipolar DC distribution networks," in *IEEE Second International Conference on DC Microgrids (ICDCM)*, 2017. <https://doi.org/10.1109/icdcm.2017.8001052>
- [13] A. Garcés, O.-D. Montoya, "A Potential Function for the Power Flow in DC Microgrids: An Analysis of the Uniqueness and Existence of the Solution and Convergence of the Algorithms," *Journal of Control, Automation and Electrical Systems*, vol. 30, pp. 794-801, 2019. <https://doi.org/10.1007/s40313-019-00489-4>
- [14] L. Mackay, R. Guarnotta, A. Dimou, G. Morales-Espana, L. Ramirez-Elizondo, P. Bauer, "Optimal Power Flow for Unbalanced Bipolar DC Distribution Grids," *IEEE Access*, vol. 6, pp. 5199-5207, 2018. <https://doi.org/10.1109/access.2018.2789522>
- [15] J.-O. Lee, Y.-S. Kim, S.-I. Moon, "Current Injection Power Flow Analysis and Optimal Generation Dispatch for Bipolar DC Microgrids," *IEEE Transactions on Smart Grid*, vol. 12, pp. 1918-1928, 2021. <https://doi.org/10.1109/tsq.2020.3046733>
- [16] J. Kim, J. Cho, H. Kim, Y. Cho, H. Lee, "Power Flow Calculation Method of DC Distribution Network for Actual Power System," *KEPCO Journal on Electric Power and Energy*, vol. 6, pp. 419-425, 2020. <https://doi.org/10.18770/KEPCO.2020.06.04.419>
- [17] O. D. Montoya, Á. Medina-Quesada, W. Gil-González, "Solving the Power Flow Problem in Bipolar DC Asymmetric Distribution Networks Using Broyden's Method," *Sensors*, vol. 23, e6704, 2023.

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- [18] J.-O. Lee, Y.-S. Kim, J.-H. Jeon, "Generic power flow algorithm for bipolar DC microgrids based on Newton–Raphson method," *International Journal of Electrical Power & Energy Systems*, vol. 142, e108357, 2022.
- [19] S. Sepúlveda-García, O. D. Montoya, A. Garcés, "A second-order conic approximation to solving the optimal power flow problem in bipolar DC networks while considering a high penetration of distributed energy resources," *International Journal of Electrical Power & Energy Systems*, vol. 155, e109516, 2024.
- [20] C. Hernandez, W. Sánchez Huertas, V. Gómez, "Optimal Power Flow through Artificial Intelligence Techniques," *Tecnura*, vol. 25, pp. 150-170, 2021. <https://doi.org/10.14483/22487638.18245>
- [21] O. D. Montoya, V. M. Garrido, W. Gil-Gonzalez, L. F. Grisales-Norena, "Power Flow Analysis in DC Grids: Two Alternative Numerical Methods," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, pp. 1865-1869, 2019. <https://doi.org/10.1109/tcsii.2019.2891640>
- [22] O. D. Montoya, W. Gil-González, A. Garcés, "A successive approximations method for power flow analysis in bipolar DC networks with asymmetric constant power terminals," *Electric Power Systems Research*, vol. 211, e108264, 2022. <https://doi.org/10.1016/j.ijepes.2020.106299>
- [23] A. Garcés, "On the Convergence of Newton's Method in Power Flow Studies for DC Microgrids," *IEEE Transactions on Power Systems*, vol. 33, pp. 5770-5777, 2018. <https://doi.org/10.1109/tpwrs.2018.2820430>
- [24] M. C. Herrera-Briñez, O. D. Montoya, L. Alvarado-Barrios, H. R. Chamorro, "The Equivalence between Successive Approximations and Matricial Load Flow Formulations," *Applied Sciences*, vol. 11, e2905, 2021. <https://doi.org/10.3390/app11072905>
- [25] L. Paniagua, R. B. Prada, "Voltage stability assessment using equivalent Thevenin," in *IEEE Thirty Fifth Central American and Panama Convention (CONCAPAN XXXV)*, 2015. <https://doi.org/10.1109/concapan.2015.7428499>
- [26] O. D. Montoya, W. Gil-González, A. Garcés, "Numerical methods for power flow analysis in DC networks: State of the art, methods and challenges," *International Journal of Electrical Power & Energy Systems*, vol. 123, e106299, 2020.
- [27] J. W. Simpson-Porco, F. Dorfler, F. Bullo, "On Resistive Networks of Constant-Power Devices," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 62, pp. 811-815, 2015. <https://doi.org/10.1109/tcsii.2015.2433537>
- [28] P. Huamaní Navarrete, "Programación de interfaz gráfica en APP Designer del MATLAB para representar la serie de Fourier en curso introductorio de telecomunicaciones," *Scientia*, vol. 23, pp. 199-213, 2023. <https://doi.org/10.31381/scientia.v23i23.4592>
- [29] D. Murillo-Yarce, A. Garcés-Ruiz, A. Escobar-Mejía, "Passivity-Based Control for DC-Microgrids with Constant Power Terminals in Island Mode Operation," *Revista Facultad de Ingeniería Universidad de Antioquia*, pp. 32-39, 2018. <https://doi.org/10.17533/udea.redin.n86a05>