20th International Conference on Renewable Energies and Power Quality (ICREPQ'22)
Vigo (Spain), 27th to 29th July 2022
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2022

Performance analysis of power flow strategies adjusted to a distribution network with non-linear loads and a PV system

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Abstract. In analysing power flows, computational strategies and tools are used to study electrical networks considered ill-conditioned by characteristics such as radial topology, load unbalance, and distributed generation. However, these techniques do not consider harmonic distortion that power electronics devices recently injected into electrical networks. For this reason, this work presents a comparison of the results of three strategies for solving harmonic power flows, where each one of them uses a specific load model in the frequency domain to represent non-linear loads and a photovoltaic system installed in a distribution network. The traditional Backward/Forward algorithm is adjusted to meet the characteristic conditions of the network. It applies the Norton equivalent coupled admittance matrix model. The other strategies model the electrical network in specialised software; the analysis in Simulink considers the Norton decoupled admittance matrix model, while PowerFactory uses the current source model to represent the loads and the PV system. All three strategies successfully determined the waveforms of the voltage signals; however, the results showed differences for the current signals and power parameters.

Keywords. Backward/Forward, harmonics, PowerFactory, power flow, Simulink

1. Introduction

The study of power flows is a tool that allows analysing the steady-state operation of an electrical system. Generally, power flows use numerical analysis to develop the study of the operation in power systems [1].

These studies estimate the magnitude values and phase angles of node voltages and branches currents, as well as power parameters [2].

There are different methods or strategies for solving power flows, each one using different approaches [2]. An example is the methods based on sweeps, such as Backward/Forward, which have gained importance in the analysis of distribution networks since the mathematical approach used makes it easy to obtain accurate results in short computational times, and also does not have restrictions such as the methods conventional analysis of transmission systems [1], [3]–[6].

On the other hand, there are computational tools or programs such as PowerFactory by DIgSILENT or Simulink, used to analyse electrical systems at the level of generation, transmission and distribution [7]–[9].

Moreover, the solution strategies and computational tools mentioned have been adapted to the new operating conditions of electrical networks, such as integrating distributed generators and non-linear devices.

However, few studies on the analysis of harmonic power flows in the literature consider the simultaneous operation of distributed resources, load unbalance, and their non-linearity.

Similarly, the integration of non-linear devices in distribution networks demands the use of models that represent their harmonic nature [10]; likewise, such models should consider the harmonic interaction between the supply voltage and the current demanded.

Despite this, it is currently common to use models in the frequency domain that depend on the fundamental frequency, such as the current source model, which does not consider the harmonic interaction between voltage and current [2], [11]–[14].

In this sense, this article presents a comparison of the performance of three power flow solution strategies that each one applies a different load model in the frequency domain, Backward/Forward uses the Norton equivalent model with coupled admittance matrix (BF-NC), Simulink uses the equivalent Norton model with decoupled admittance matrix (S-ND). Finally, PowerFactory uses the Current Source (PF-FC) model.

The analysis of the performance of the strategies consists of comparing the results of waveforms and power parameters of the main nodes of a distribution network of a university building, which has non-linear lighting and ventilation loads installed, and a photovoltaic (PV) system.

2. Strategies description

This section describes the power flow estimation strategies adapted to the characteristics of a distribution network with non-linear loads and the power injection of a PV system.

A. Backward/Forward

Backward/Forward is a swept-type power flow solution strategy applied mainly to radial topology distribution networks, considering an unbalanced network operation due to the presence of single-phase, two-phase and three-phase loads.

Likewise, the strategy has been adapted to solve harmonic power flows, differentiating the mathematical models used to represent the behaviour of linear and non-linear loads [1], [2], [4]–[6].

Figure 1 describes the Backward/Forward algorithm based on Kirchhoff's laws adapted to the characteristic conditions of the case study network.

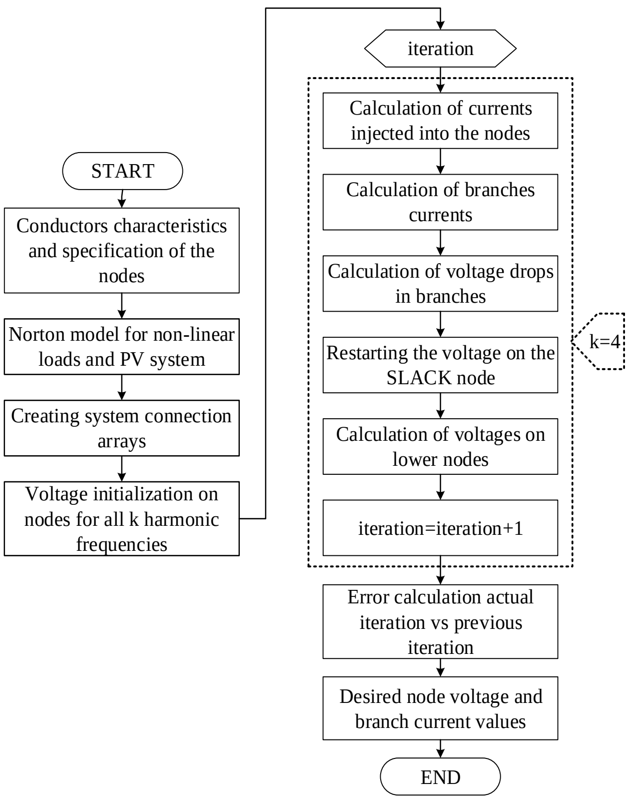


Fig. 1. Flowchart of the approach applied in Backward/Forward

The adaptations implemented were the input of the Norton model for non-linear loads and the PV system, the initialization of the voltage of the node for the *k* harmonic frequencies and the calculations of the iterative process for each *k* harmonic frequency.

It should be noted that the third, fifth and seventh harmonic orders were the harmonic frequencies selected to carry out the study due to the representativeness they have in the voltage signal of the feeder of the building's electrical network. Therefore, the value of *k* is 4.

B. PowerFactory

PowerFactory allows analysis of harmonic power flows using the non-iterative harmonic penetration approach [15], assuming the process is divided into two stages. The first stage comprises a power flow at fundamental frequency; the second stage comprises the power flows at harmonic frequencies.

The load model used to represent the loads installed in the electrical network depends on the fundamental frequency of the system. In the case of non-linear loads, the technique uses the Current Source model, which does not consider the harmonic interaction between the voltage and current signals.

Figure 2 presents the flowchart of the procedure implemented in PowerFactory to simulate the electrical network case study. First, the elements that make up the network are configured: an external network, the nodes, the branches, and the loads.

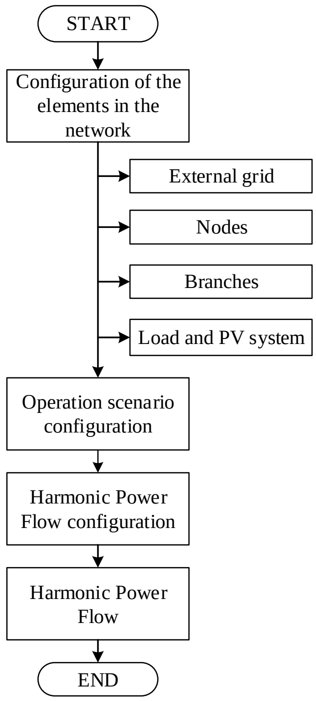


Fig. 2. Flowchart of the approach applied in PF

C. Simulink

Simulink is a computational tool that allows solving power flows from the approach and solution of the equations of state of the model in the frequency domain.

The electrical network of the case study was modelled in the tool, considering the use of the decoupled Norton model for the representation of the loads and the PV system.

The modelling took into account the characteristics of the network and the orders of the most representative harmonic components (third, fifth and seventh). For this reason, the network is represented by four subsystems, one per frequency, as shown in Figure 3.

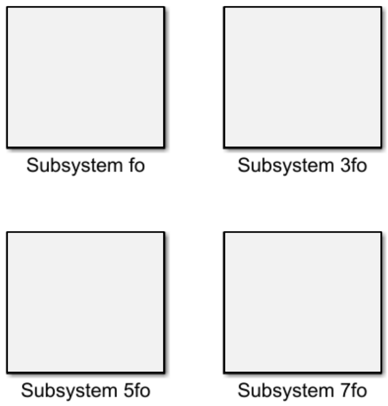


Fig. 3. General structure of the Simulink model

3. Study case

The power flow solution strategies were adapted to the characteristics and operating conditions of a low voltage distribution network.

The electrical network belongs to the distribution panel on the 4th floor of the Electrical Engineering Building of the Universidad Industrial de Santander (UIS), located in Bucaramanga, Colombia.

Figure 4 shows the single-line diagram of the network of floor 4 of the building, where lighting and ventilation loads are installed. Also, it is the common coupling point (PCC) between the electrical network of the building and the PV system.

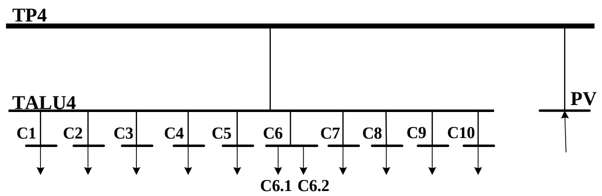


Fig.4. Single-phase diagram of the study case grid

The electrical network consists of two sub-panels, TALU4 and PV. Lighting and ventilation loads are connected to the TALU4 subpanel. On the other hand, the PV sub-panel is the PCC between the power grid and the PV system.

Table I shows the general characteristics of the mentioned loads and the PV system.

Table I. General characteristics of the loads and PV system

DEVICE	RATED POWER	CONTROL	LOCATION AND PHASE
On-Off luminaire	68 W Single-phase	On-Off	C5-BN
Dimmable luminaire	70 W Single-phase	Dimmable (0 a 10 Vdc)	C1- AN; C2- BN; C3- CN; C4- AN; C6.1- CN
Air extractor	66 W Single-phase	-	C6.2- CN; C7- AN; C8- BN; C9- CN; C10- AN
PV system	Phase A 4620 W Phase B 4080 W Phase C 3255 W	-	PV ABC-N

A. Devices modelling

The SLACK node or node of infinite power represents the transformer of the electrical network of the building, which has a capacity of 630 kVA, 13.2 kV/220 V and Δyn5 connection. The nominal phase voltage value of the node is 127 V.

On the other hand, the modelling of elements such as conductors, non-linear loads and the PV system took into account their dependence on changes in frequency. Therefore, models in the frequency domain were considered for their representation.

In the case of electrical conductors, these are represented by a frequency-dependent series impedance RL as indicated by Eq. (1), where h indicates the harmonic order of the frequency under study.

$$Z_h = R + jhX_L \tag{1}$$

The non-linear loads and the PV system were represented in the frequency domain with the Norton equivalent model with the coupled admittance matrix (Backward/Forward), decoupled admittance matrix (Simulink) and the current source model (PowerFactory).

On-Off luminaires and air extractors have a single operating condition. In contrast, dimmable luminaires have two operating states depending on the dimming level (0Vdc and 10Vdc). Finally, the PV system has three operating conditions according to solar irradiance Ginc (high, medium and low). Only two states of operation, high and low, were considered in the study [16]–[18].

B. Operation scenarios

Considering the operation of each load and the PV system were proposed some scenarios. Table II presents the operation scenarios taking into account the operation of each device.

Table II. Operation scenarios

	Luminaire						Air Extractor		PV	
	On-Off		Dimmable							
	Min	Max	Min		Max		Min	Max	H	B
			0Vdc	10Vdc	0Vdc	10Vdc				
E1	✓		✓						✓	
E2	✓			✓						✓
E3		✓			✓				✓	
E4		✓				✓				✓
E6							✓			✓
E8							✓		✓	
E9								✓		✓
E11								✓	✓	
E12									✓	
E14										✓
E15	✓		✓				✓		✓	
E16	✓			✓			✓			✓
E17		✓			✓		✓		✓	
E18		✓				✓	✓			✓
E19	✓		✓					✓	✓	
E20	✓			✓				✓		✓
E21		✓			✓			✓	✓	
E22		✓				✓		✓		✓

4. Results

This section presents the results obtained estimating the voltage and current signals. Likewise, it presents the performance of the waveform errors of the voltage and current signals and the percentage errors of active and non-active power.

A. Waveforms

Figure 5 shows the waveforms of each strategy's voltage signals compared with the SLACK node's waveform. A predominance of a flat-top waveform is observable, in which the third and seventh harmonic orders prevail.

Moreover, a similarity of the voltage signals of the three strategies with the voltage signal of the SLACK node is observable, regardless of the operating scenario under study.

Now, figures 6 and 7 show the waveforms of the current signals of the TP4-TALU4 and TP4-PV branches for the high and low solar irradiance scenarios.

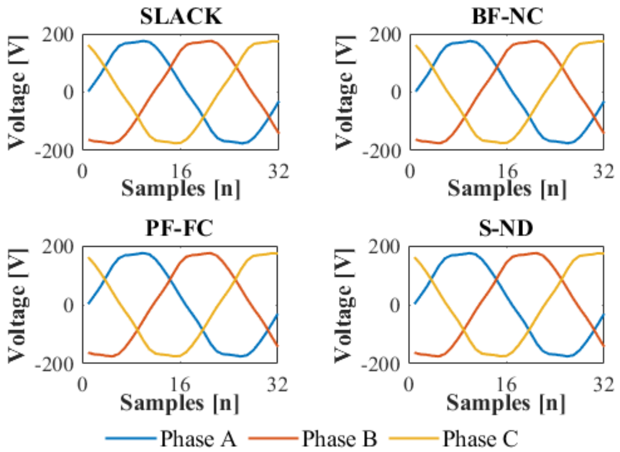
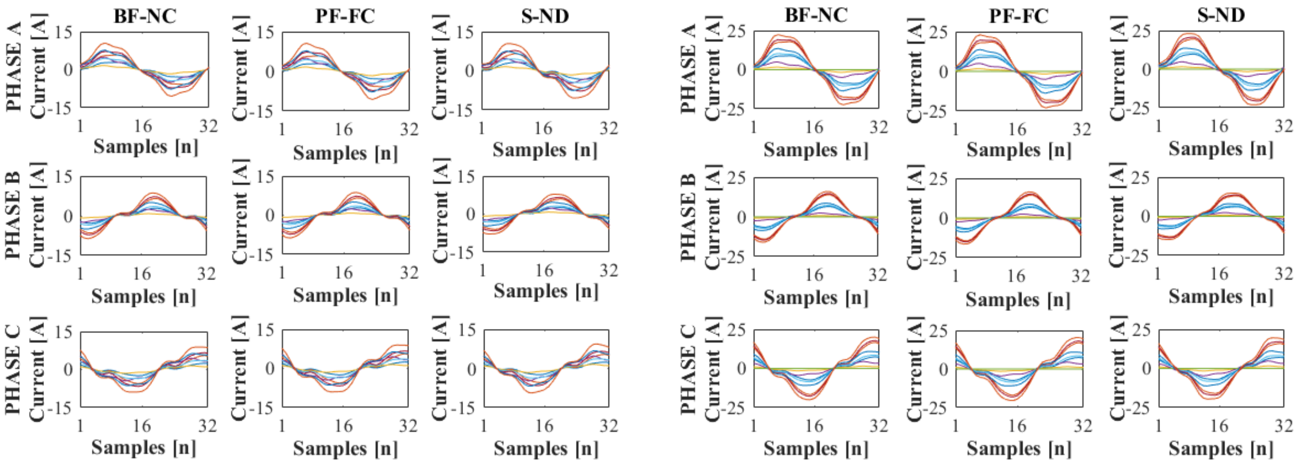


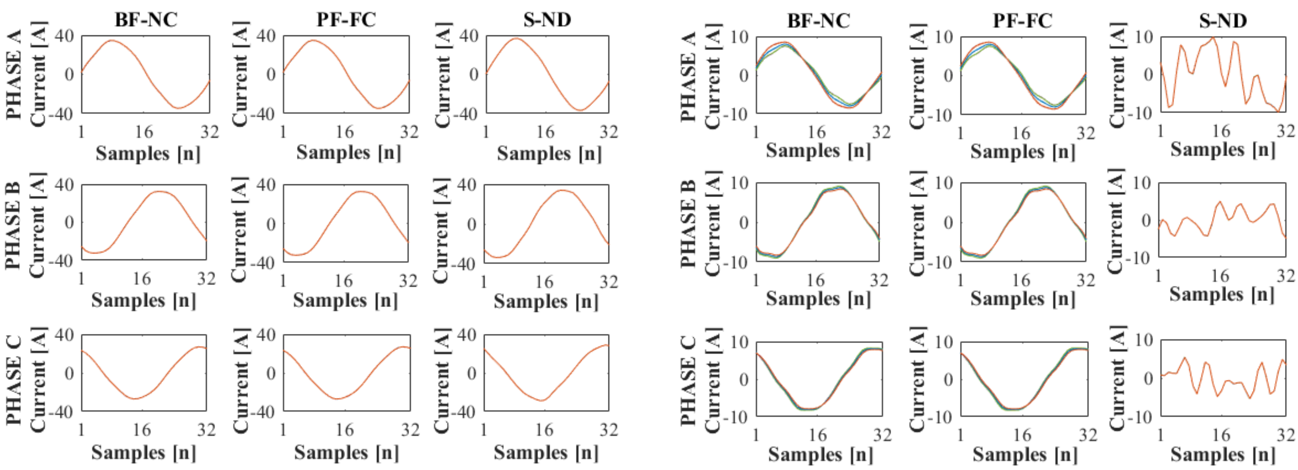
Fig. 5. Voltage signal waveforms

In Figure 6, a difference in the amplitude of the current signals is observable due to the close relationship between the dimming levels of the luminaires, the levels of solar irradiance and, therefore, the operation of the PV system.



a) High G_{inc} (E1, E3, E8, E11, E12, E15, E17, E19, E21). b) Low G_{inc} (E2, E4, E6, E9, E14, E16, E18, E20, E22).

Fig. 6. Current signal waveforms on the TP4-TALU4 branch for all operating scenarios



a) High G_{inc} (E1, E3, E8, E11, E12, E15, E17, E19, E21). b) Low G_{inc} (E2, E4, E6, E9, E14, E16, E18, E20, E22).

Fig. 7. Current signal waveforms on the TP4-PV branch for all operating scenarios

On the other hand, Figure 7 shows the differences in the operation of the PV system in the two levels of solar irradiance. For high solar irradiance scenarios, where the PV system injects its maximum power, the strategies estimate a current waveform similar to a sinusoidal one.

However, the BF-NC and PF-FC strategies show slightly noticeable differences at low solar irradiance levels. At the same time, the current signals estimated by S-ND are entirely distorted.

Table III presents a summary of the performance analysis of the NRMSE waveform errors of the voltage and current signals of the power flow solution strategies.

In the case of the voltage signal, the strategies obtained an excellent and satisfactory performance, having error values less than 0.04% for high irradiance and 0.08% for low irradiance.

On the contrary, the performance of the Simulink strategy is poor when estimating the waveforms of current signals in operating scenarios where low solar irradiance is considered. The cause of this is the poor accuracy in estimating the current signal by the Norton decoupled admittance matrix model.

Table III. Performance of the waveforms errors

	NODE	Voltage		BRANCH	Current	
		HGinc	LGinc		HGinc	LGinc
BF-NC	Performance	✓✓✓✓✓	✓✓✓✓✓	Performance	✓✓✓✓✓	✓✓✓✓✓
S-ND	Performance	✓✓✓✓✓	✓✓✓✓✓	Performance	✓✓✓	✓
S-ND	Maximum error	**0.04%**	**0.05%**	Maximum error	**4.7%**	**41%**
S-ND	TP4	<0.04%	<0.05%	SLACK-TP4	<2.3%	<41%
S-ND	TALU4	<0.04%	<0.05%	TP4-TALU4	<4.7%	<3.3%
S-ND	SFV	<0.04%	<0.05%	TP4-PV	<2.3%	<41%
PF-FC	Performance	✓✓✓✓✓	✓✓✓✓✓	Performance	✓✓✓✓	✓✓✓
PF-FC	Maximum error	**0.04%**	**0.08%**	Maximum error	**0.4%**	**1.1%**
PF-FC	TP4	<0.02%	<0.05%	SLACK-TP4	<0.2%	<0.8%
PF-FC	TALU4	<0.04%	<0.08%	TP4-TALU4	<0.4%	<1.1%
PF-FC	SFV	<0.02%	<0.05%	TP4-PV	<0.2%	<0.2%

Note: ✓- Poor, ✓✓- Regular, ✓✓✓- Acceptable, ✓✓✓✓- Good, ✓✓✓✓✓- Excellent.

B. Power parameters

Table IV shows the performance of the power flow solution strategies in terms of active and non-active power.

The PowerFactory solution strategy has an acceptable performance in the two power parameters studied, with errors no greater than 3.2% in active power and 3% in non-active power.

On the contrary, the Simulink strategy presents a poor performance with errors higher than 10% in low irradiance scenarios in active power and for all the scenarios studied in the case of the non-active power parameter.

The previous confirms what was established with the waveform errors of the current signals for the Simulink strategy. The decoupled admittance matrix Norton model has a significant impact on estimating electrical variables and parameters of an electrical network.

Table IV. Performance of the power parameters errors

	BRANCH	P		Q	
		HGinc	LGinc	HGinc	LGinc
BF-NC	Performance	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓
S-ND	Performance	✓✓✓	✓	✓	✓
S-ND	Maximum error	**4.5%**	**89%**	**55%**	**1500%**
S-ND	SLACK-TP4	<4.5%	<89%	<27%	<390%
S-ND	TP4-TALU4	<0.4%	<0.3%	<55%	<84%
S-ND	TP4-PV	<4.5%	<89%	<14%	<1500%
PF-FC	Performance	✓✓✓	✓✓✓	✓✓✓	✓✓✓
PF-FC	Maximum error	**1.3%**	**3.2%**	**3%**	**3%**
PF-FC	SLACK-TP4	<0.6%	<2.2%	<2%	<2%
PF-FC	TP4-TALU4	<1.3%	<3.2%	<3%	<3%
PF-FC	TP4-PV	<0.4%	<0.3%	<0.4	<0.6%

Note: ✓- Poor, ✓✓- Regular, ✓✓✓- Acceptable, ✓✓✓✓- Good, ✓✓✓✓✓- Excellent.

5. Conclusions

This work evaluates the performance of three power flow solution strategies. Each strategy employs a different load model in the frequency domain. The detailed analysis showed that the load model used in the harmonic power flow influences and impacts the performance of the strategies in terms of estimating variables and electrical parameters.

The NRMSE errors of the voltage signals of the three strategies showed an excellent performance with errors less than 0.1%. Therefore, it is stated that the three approaches satisfactorily estimate the voltage signal. Considering the NRMSE errors of the current signals is possible to affirm that in high solar irradiance scenarios, the strategies acceptably estimate the current signals, with errors of less than 5%. However, for low solar irradiance operation, the performance of the Simulink and PowerFactory strategies is unsatisfactory, with maximum errors of 41% and 1.1%, respectively.

In terms of power parameters, the maximum errors obtained by the PowerFactory strategy do not exceed 3.2%, considering an acceptable performance. However, analysing the Simulink strategy, there are maximum active power errors of 89% and non-active power of 1500% for the case of low solar irradiance operating scenarios. On the contrary, the maximum errors for high solar irradiance scenarios are 4.5% in active power and 55% in non-active power. Therefore, the performance of the power flow estimation strategies is regular.

Finally, the power flow solution strategies analyzed can be adjusted and applied to electrical networks with characteristics similar to the network taken as a case study. Also, there is a possibility of integrating another distributed resource into their analysis.

Acknowledgement

The authors wish to thank the Department of Electrical, Electronics and Telecommunications Engineering (Escuela de Ingenierías Eléctrica, Electrónica y de Telecomunicaciones), the Vice-Rectorate for Research and Extension (Vicerrectoría de Investigación y Extensión) from the Universidad Industrial de Santander (Projects 2705 and 8593), and the Minister of Science, Technology and Innovation (Ministerio de Ciencia, Tecnología e Innovación) – COLCIENCIAS (Project – Contract No. 80740-191-2019 – Funding resource).

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