Disturbance Analysis and Protection Performance Evaluation

F. V. Lopes, D. Barros, R. Reis, C. Costa, J. Nascimento, N. Brito, W. Neves and S. Moraes

Abstract—**This paper presents the evaluation of the first module of a software for disturbance diagnosis and protection performance analysis, which is being developed by the São Francisco's Hydroelectric Company (CHESF) in partnership with the Federal University of Campina Grande (UFCG) and researchers from other Brazilian institutions. This software was named DAPPE (Disturbance Analysis and Protection Performance Evaluation) and it is able to extract basic information about short-circuits and performances of certain protection functions. In order to evaluate DAPPE routines, actual oscillographic fault records provided by CHESF were analyzed and digital short-circuit simulations in the Alternative Transients Program (ATP) and in the Computed-Aided Protection Engineering (CAPE) software were performed. The obtained results show that the DAPPE's first module is reliable and it will be useful for CHESF during disturbance analysis and protection performance evaluation procedures.**

Keywords: **ATP, CAPE, disturbance analysis, power systems, protection systems, transmission lines.**

I. Introduction

SINCE the early stages of power networks, protection devices have played a very important role in transmission systems. Protection reliability, selectivity and security are of utmost importance in the tripping process to prevent blackouts in big areas and to ensure the protection of the equipment connected to the power grid [1]. For this purpose, utilities have demonstrated great interest on computer programs and digital devices able to evaluate the performance of protection systems from the analysis of fault records taken from digital relays or digital fault recorders (DFRs). A suitable analysis of measured signals can clarify cases in which digital relays misoperate, identifying, for instance, whether these devices have been incorrectly set in the field [2].

In Brazil, when faults on transmission systems occur, utilities must send a disturbance report, called Protection Performance Analysis Report (PPAR), to regulatory organizations, which evaluate the power grid operation procedures. For this purpose, in 2013, the São Francisco's Hydroelectric Company (CHESF), which is located in Brazil, signed a research contract in partnership with the Federal University of Campina Grande (UFCG) and researchers from other Brazilian institutions to develop a software named DAPPE (Disturbance Analysis and Protection Performance Evaluation). The main goal of DAPPE is to give support for protection engineers during the preparation of the PPAR, providing part of it automatically.

The first module of DAPPE was completed in 2014. It is able to read COMTRADE files, to detect, classify and locate faults, as well to estimate phasors and the circuit breakers (CBs) opening time. Also, DAPPE has distance protection functions based on both mho element (self-polarized and polarized ones) and quadrilateral element (self-polarized one) [3]. In this paper, the methodology used by DAPPE to diagnose faults and analyze the protection performance is evaluated. Initially, to validate the DAPPE routines, digital fault simulations in a 230 kV transmission system are performed by using the Alternative Transients Program (ATP) and the Computed-Aided Protection Engineering (CAPE). Then, actual records provided by CHESF are analyzed.

The obtained results attest that the first module of DAPPE is reliable. In the cases in which the relay was correctly set, the trip signal was generated by DAPPE as expected. On the other hand, in cases for which the relay was incorrectly configured, the software indicated a misoperation. Likewise, when actual records were evaluated, the disturbance diagnosis reports were in agreement with the PPARs provided by CHESF, highlighting the software reliability and effectiveness for disturbance diagnosis and protection evaluation procedures.

II. DAPPE

Recent advancements in digital technologies have allowed DFRs and numerical relays to capture voltage and current waveform samples reliably and accurately. In fact, different from the past, data-acquisition systems are not a problem anymore [4], what has allowed further developments in the protection area, increasing the interest of utilities for methodologies, computer programs and devices for disturbance diagnosis and protection performance evaluations.

In 2013, the Brazilian National Electric Energy Agency (ANEEL) issued a note in which the assessment of protection systems operating in 124 substations was requested [5]. Hence, to help CHESF engineers to carry out evaluations of disturbances and protection systems' performance, DAPPE has been developed since 2013, focusing on the study of faults in transmission systems.

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In the literature, there are some strategies for the assessment of data taken from DFRs and numerical relays for fault diagnosis and protection performance evaluation purposes [6]. However, most of these solutions are not editable, what makes it impossible to adapt their adjustments to different devices and utility needs. In this context, DAPPE is presented as a great tool for CHESF, since it is being developed in accordance to the interests of the utility departments responsible for fault diagnosis and protection performance analysis. The final version of DAPPE will automatically generate a report with relevant information about short-circuit cases, such as: fault location, distance protection tripping data, CB opening time, among others. This report will contain information typically used in the technical reports PPAR mentioned before, greatly facilitating its preparation. In Fig. 1, the block diagram of DAPPE is illustrated.

The input signals used by DAPPE are taken from numerical relay analog and digital channels, which provide information about voltage and current waveforms, and about the on/off data of protection functions. These signals must be taken from at least one protection device installed on the faulty line and the records should contain, besides voltage and current data, information about protection trip signals. By using these information, DAPPE generates a report, which is divided into two parts: the disturbance diagnosis report and protection performance report (Fig. 1).

Basically, DAPPE runs routines similar to those in relays that implement the protection functions chosen to be evaluated. Thus, it is able to estimate basic disturbance features and tripping signals of the implemented protection functions, generating the disturbance diagnosis report. These estimated tripping signals are treated here as *expected relay tripping signals*, which are compared with the actual tripping signals taken from the relay digital channels. From this comparison, the protection performance report is built, making possible the process of identifying cases in which relays misoperate and providing a starting point for the fault analysis. Obviously, protection functions implemented in DAPPE will never be equal to those in the relay. Even so, the most relevant information about protection performance and disturbance features can be reliably estimated using similar, but not identical routines. This is enough to generate an initial sketch of the PPAR.

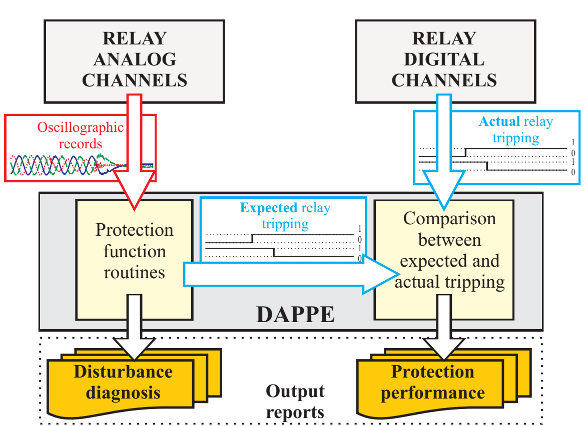

Fig. 1. DAPPE block diagram.

DAPPE's first module routines are implemented so far in the Matlab environment. A brief description of the implemented functions is presented next.

A. Phasor Estimation

Fundamental phasors are estimated using the Full Cycle Discrete Fourier Transform with a mimic filter for decaying DC component elimination [7], [8]. Such algorithm is called here as FCDFT+MIMIC and its frequency response is shown in Fig. 2. Although these algorithms are consolidated, it is intended to evaluate possible benefits on the use of other phasor estimation techniques, such as the modified cosine filter, which has been successfully used in actual relays [9].

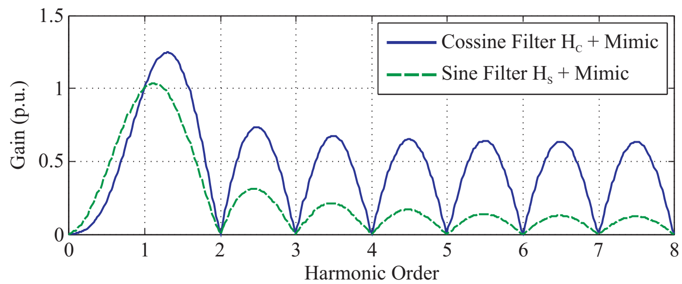

Fig. 2. Frequency response of the FCDFT+Mimic filters.

B. Disturbance Detection

This function is crucial for DAPPE, since the other algorithms implemented are triggered by such detection. The goal of this routine is to indicate that the system is no longer in its steady-state and a fault may has occurred. In DAPPE, the algorithm reported in [10] is used, as it has shown to be able to quickly detect faults in the initial moments of the disturbance, irrespective of the sampling rate used. The algorithm is based on Park's transformation, so that it is able to detect a disturbance inception whenever relevant imbalance or high frequency components appear in the monitored voltage and current signals [10]. Besides, the algorithm uses adaptive thresholds, what greatly improves the accuracy of the estimated fault inception instant.

C. Fault Classification

Fault type information is typically found in PPARs written by all utilities. For this purpose, it is necessary to classify faults among 11 possible types: Single-phase-to-ground faults (AG, BG, CG), double-phase faults (AB, AC, BC), double-phase-to-ground faults (ABG, ACG, BCG) and three-phase faults (ABC and ABCG for unbalanced systems).

In DAPPE, the overcurrent method is used for fault classification [11]. From the literature, it is known that this method is not the most robust for applications in real-time, but it presents a good performance in off-line procedures, in which the thresholds can be adjusted in accordance to the higher fault current value. Even so, other solutions have been investigated, so that, in future works, it is intended to improve this function in DAPPE. Fig. 3 illustrates the fault classification procedure.

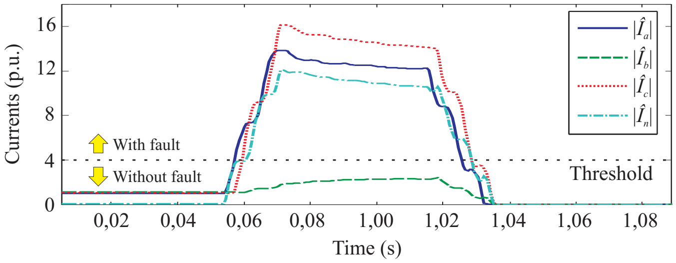

Fig. 3. Fault type classification procedure.

D. Fault Location

To perform the fault location, one-terminal methods are used in DAPPE. By using one-terminal algorithms, the need of synchronized records is eliminated [12], making the DAPPE application easier. Fault location is estimated from the impedance seen by the relay during short-circuits. It is normalized and then expressed in kilometers. Each fault distance is computed taking the terminal from which the oscillographic records are being taken as reference. Two-terminal techniques have been also investigated and will be included in DAPPE in the next steps of the research.

E. CB Opening Detection

DAPPE detects the CB opening through the comparison between the absolute values of current fundamental phasors and a threshold computed from current phasor values during the normal operation of the system. Fig. 4 shows how this procedure is performed. This solution considers that the magnitude of currents in opened phases drops to zero after the electrical and mechanical separation of the CB poles. By doing so, one can provide a more accurate CB opening detection than when the analysis of CB auxiliary contacts is performed. It is known that these auxiliary contacts typically present intrinsic delays, which can lead the CB opening detection procedure to present relevant errors, jeopardizing the DAPPE performance.

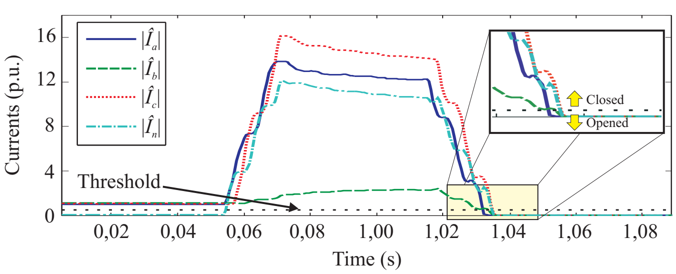

Fig. 4. CB opening detection procedure.

F. CB Opening Time

DAPPE computes the CB opening time as the period between the disturbance detection instant and the moment in which the CBs open. Users of DAPPE can also choose whether the CB opening time is computed as aforementioned, or using as reference the moment in which the implemented distance protection functions detect a fault into zones 1 or 2 in the monitored transmission line.

G. Distance Protection

The distance protection was the first function embedded in DAPPE. Self-polarized mho element, polarized mho element using positive sequence voltage memory and self-polarized quadrilateral element are implemented [3]. The behavior of these functions is depicted in the DAPPE output report, allowing a more precise disturbance and protection performance analysis. Phase selection procedure takes into account the output of the fault classification stage of DAPPE and phase comparators are used to distinguish the fault period from the steady-state [3]. In DAPPE, one can set values for the reaching of the protected zones 1 and 2, mho element torque angle, reaching of the quadrilateral resistive element and the quadrilateral directional element slope. The remaining parameters, such as the slope of quadrilateral reactance and resistive elements, are set using typical values [3], [13].

III. DAPPE Evaluation

The evaluation of DAPPE's first module is divided in two parts. Firstly, fault records taken from ATP and processed in CAPE are analyzed. Secondly, actual fault records provided by CHESF are evaluated and the obtained results are compared with those available in the PPARs of each disturbance.

A. DAPPE Evaluation Using ATP and CAPE

In the first DAPPE evaluation part, simulated records are analyzed in order to allow the study of cases not available in the actual records provided by CHESF. The ATP is used to generate voltage and current waveform signals, representing the relay analog channels. These data are imported by CAPE to generate the relay tripping signals, i.e., it represents the relay digital channels. Fig. 5 illustrates how these simulations were done respecting the DAPPE structure (Fig. 1). An actual model of a distance relay was used in CAPE [14], [15].

After each simulation, the expected relay tripping estimated via DAPPE was compared with the "actual" relay tripping signals, which are those obtained from CAPE simulations considering as the correct settings: a zone 1 reaching of 80% of the line positive-sequence impedance and a torque angle of 60° (for the mho element only).

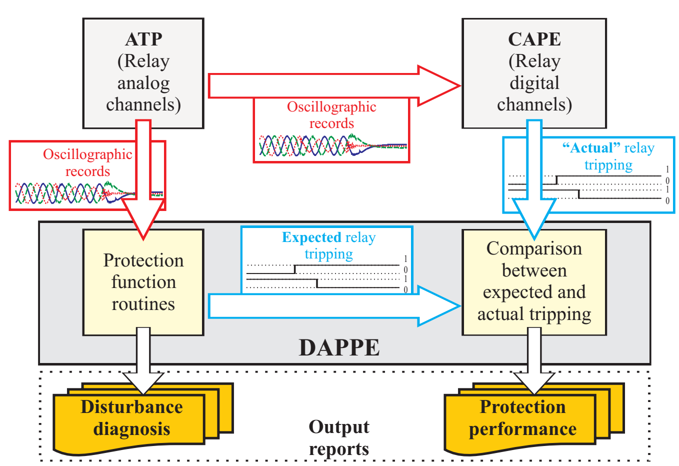

Fig. 5. DAPPE block diagram for disturbance analysis using ATP and CAPE.

CAPE was chosen because it has several models of actual relays available, which are supplied by the manufacturers themselves. As a consequence, simulations become quite realistic, allowing a reliable evaluation of cases that are difficult to be reproduced in the field without compromising the power system operation. Fig. 6 shows the power system modeled in ATP to simulate faults. It is a 230 kV system, which has been proposed by the IEEE in [16] for transmission line relaying studies. The power system consists in two parallel transmission lines 150 km long each (TL 1 and TL 2); a single circuit transmission line 150 km long (TL 3) and two Thévenin equivalent circuits connected to buses 1 and 3. The coupling capacitor voltage transformers (CCVTs) and current transformers (CTs) were intentionally modeled as ideal instrument transformers, in order to allow the evaluation of DAPPE functions itself.

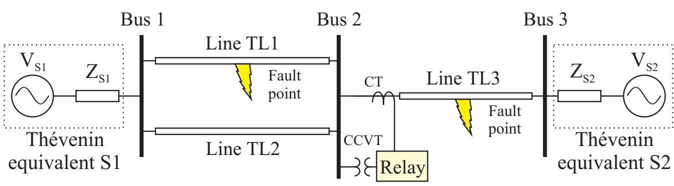

Fig. 6. 230 kV test power system.

Faults were applied in transmission lines TL1 and TL3 to analyze cases of external and internal faults to the line TL3, respectively. Several cases were simulated, but, for simplification, results of 15 fault cases are presented. The obtained results are separated in accordance to the fault type, resulting in four sets of cases: single line-to-ground faults, line-to-line faults, double-line-to-ground faults and three-phase faults. Also, a fifth set of cases is analyzed, in which relays in CAPE are intentionally put to operate with incorrect setup in order to simulate possible human errors during numerical relay setting. Besides the fault type, in each simulation, different values of fault resistance, fault inception angle and fault location were considered.

Table I describes the analyzed cases and Figs. 7 to 10 show the obtained results. Only self-polarized mho and quadrilateral elements are shown in these figures, since the polarized ones vary dynamically during the disturbance, making its graphical representation more complicated.

TABLE I
SIMULATED FAULT CASES.

Set of cases	Fault Description
Single-line-to-ground faults	AG, Zone 1, 25 km, 10 Ω, 30°
	BG, Zone 2, 150 km, 20 Ω, 0°
	CG, External (in TL 1), 150 km, 1 Ω, 60°
Line-to-line faults	AB, Zone 1, 75 km, 1 Ω, 0°
	BC, Zone 2, 125 km, 10 Ω, 30°
	AC, External (in TL 1), 125 km, 10 Ω, 60°
Double-line-to-ground faults	BCG, Zone 1, 50 km, 20 Ω, 90°
	ACG, Zone 2, 125 km, 1 Ω, 60°
	ABG, External (in TL 1), 100 km, 1 Ω, 0°
Three-phase faults	ABC, Zone 1, 25 km, 10 Ω, 0°
	ABCG, Zone 2, 150 km, 1 Ω, 60°
	ABC, External (in TL 1), 150 km, 1 Ω, 90°
Relays with incorrect setup	ABC, Zone 1, 25 km, 10 Ω, 0°
	(Zone 1 reaching of 60% instead of 80%)
	ABC, Zone 1, 25 km, 10 Ω, 0°
	(Torque angle equal to 75° instead of 60°)

*In this case, an incorrect setup was intentionally used in CAPE relay models, whereas DAPPE remained operating with correct configuration.

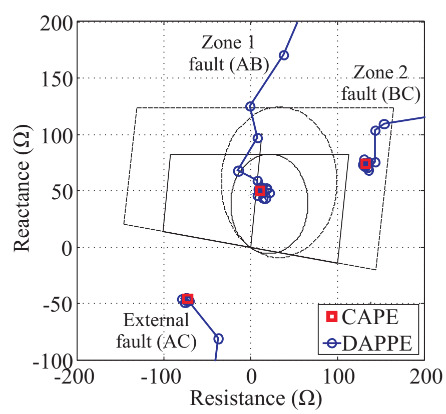

Fig. 8. Line-to-line fault simulations.

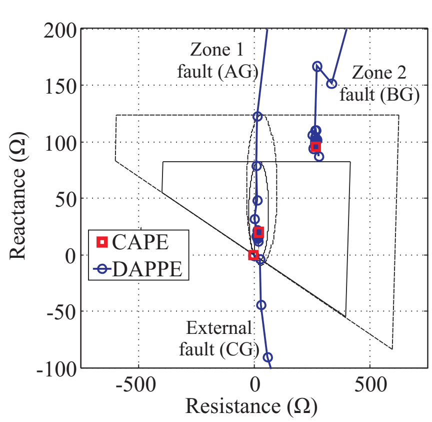

Fig. 7. Single line-to-ground fault simulations.

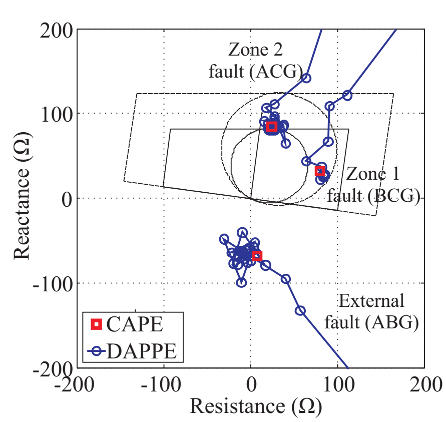

Fig. 9. Double-line-to-ground fault simulations.

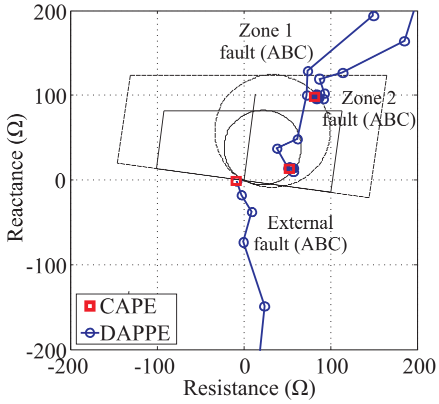

Fig. 10. Three-phase fault simulations.

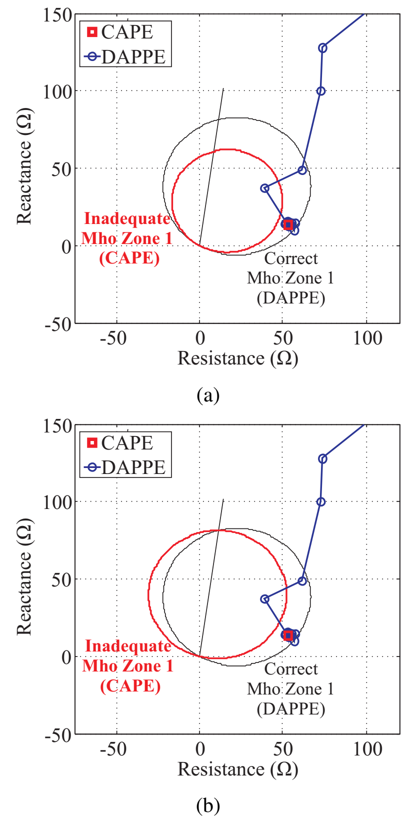

Fig. 11. Three-phase fault simulations using relays incorrectly set: (a) Zone 1 with 60% instead of 80%), (b) Torque angle equal to 75° instead of 60°.

For all fault cases in which the relay is correctly set, the results obtained via DAPPE match those obtained by CAPE, confirming that DAPPE routines are reliable. Also, it shows that differences between DAPPE algorithms and those implemented in the relay do not result in relevant tripping deviations when the analysis is performed considering voltage and current samples taken from the steady-state of the fault.

In Fig. 10, both mho and quadrilateral elements resulted in similar tripping signals. However, in Fig. 7 and 8, for BG and BC faults, respectively, the mho element did not detect the fault, whereas the quadrilateral element correctly detected a fault into zone 2. Meanwhile, in Fig. 9, for the BCG fault, the mho element detected a fault into zone 2, whereas the quadrilateral element detected the disturbance into zone 1, as expected. In these cases, the errors have occurred due to the high fault resistances (10-20 Ω). In fact, although the torque angle used in the mho element provides a better relay reaching for faults with high resistance, the quadrilateral element has the advantage of setting the reach in resistive and reactive direction independently [3], [13]. Because of this, DAPPE contains functions of both mho and quadrilateral elements, what allows the detection of short-circuits with high fault resistances when tripping signals generated by both mho and quadrilateral elements do not coincide between themselves.

Fig. 11 depicts the obtained results when the relay model in CAPE is incorrectly set. The correct parameters considered here are: mho and quadrilateral element reaching equal to 80% for zone 1, 120% for zone 2 and a torque angle equal to 60° (only for the mho element). These cases simulate human errors during the relay configuration in the field. Thus, DAPPE should be able to detect the problem and signalize that there is something incorrect in the setup. In Fig. 11(a), the zone 1 was intentionally reduced from 80% to 60% and, in Fig. 11(b), the mho element torque angle was increased from 60° to 75°.

In Fig. 11(a), owing to errors induced in the protection setup, the relay detected a fault in zone 2, when it was actually into zone 1. Furthermore, in Fig. 11(b), the relay detected a fault in zone 2, when it was actually in the zone 1. However, in both cases, DAPPE properly detected relevant differences between the estimated tripping signals and those taken from the relays in CAPE, reliably indicating a problem that could be difficult to be realized by the engineers during the disturbance and protection analysis.

B. DAPPE Evaluation Using Actual Fault Records

In this evaluation part, several actual fault records provided by CHESF were analyzed. These records were taken from numerical relays installed in 230 kV transmission systems located in Brazilian Northeast. For each evaluated case, the results obtained by using DAPPE were compared with those in the respective PPARs.

Firstly, it is performed the analysis of cases for which records from both faulty line ends are available. For this situation, faults occurred in two lines were considered: line 04S3 PAF-CCD, 133.8 km, which connects the substations Paulo Afonso II (PAF) and Cícero Dantas (CCD); and line 04F1 GNN-MRD, 50.6 km, which connects the substations Goianinha (GNN) and Mussuré II (MRD). Then, the same analysis was carried out considering cases for which records from only one terminal of the faulty line are available. Faults in four lines were studied: line 04L1 PRI-SBD, 167.50 km, which connects the substations Piripiri (PRI) and Sobral II (SBD); line 04L3 STJ-FNL, 162 km, which connects the substations Santo Antônio de Jesus (STJ) and Funil (FNL); line 04S1 TSA-PRI, 154.70 km, which connects the substations Teresina (TSA) and Piripiri (PRI); and line 04M5 CTG-CMD, 23.5 km, which connects the substations Cotegipe (CTG) and Camaçari II (CMD). The sampling rate of all relays from which the analyzed records were taken is 1440 Hz (24 samples/cycle). It should be highlighted that DAPPE is able to self-adjust its routines to different sampling frequencies, so that the user does not need to inform such data to the software.

1) Line 04S3 PAF-CCD: The short-circuit in the line 04S3 PAF-CCD occurred on July 7, 2014, due to a lightning strike, as described in the respective PPAR. Voltage and current waveform records during the disturbance are shown in Figs. 12 and 13. In Table II, the comparison between the disturbance information estimated using DAPPE and those available in the PPAR is presented.

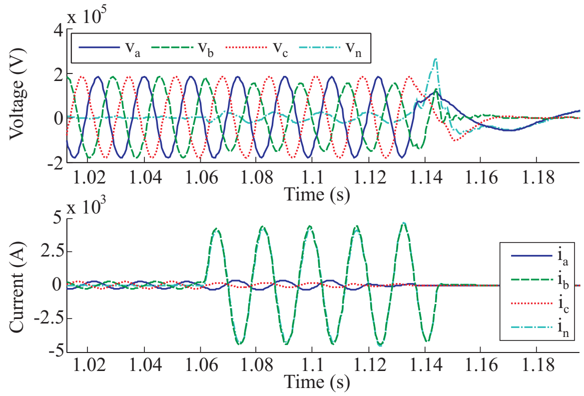

Fig. 12. Voltage and current records taken from the substation PAF.

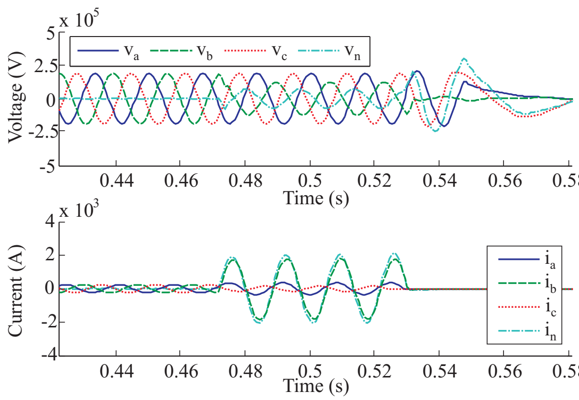

Fig. 13. Voltage and current records taken from the substation CCD.

TABLE II
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04S3 PAF-CCD.

Disturbance Data	**Substation PAF**		**Substation CCD**	
	PPAR	**DAPPE**	**PPAR**	**DAPPE**
Fault Type	BG	BG	BG	BG
Protection Tripping	Zone 1	Zone 1	Zone 1	Zone 1
CB Opening Time	83.33 ms	83.50 ms	58.33 ms	58.38 ms
Fault Location	47.3 km	48.1 km	87.8 km	88.3 km

One can see that the DAPPE report provides disturbance information quite similar to those in the PPAR. Such similarity attests that the relay operation was as expected and that it is correctly configured. Also, it shows that DAPPE routines are reliable and able to properly classify the fault, estimate the impedance seen by the relay and reliably estimate the CB opening time and the fault location.

2) Line 04F1 GNN-MRD: The transmission line 04F1 GNN-MRD was disconnected from the power system on February 24, 2012, due to an ACG short-circuit, as described in the respective PPAR. Voltage and current records during the disturbance are shown in Figs. 14 and 15. In Table III, the comparison between the DAPPE outputs and PPAR data is presented.

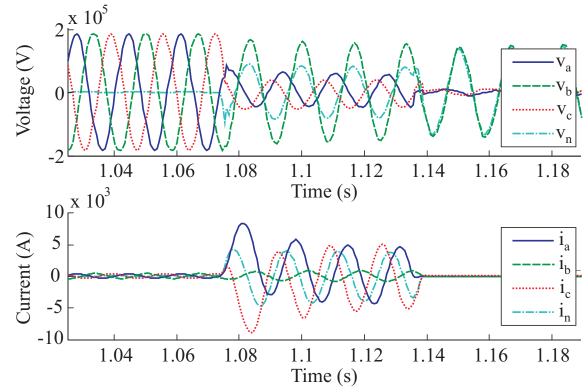

Fig. 14. Voltage and current records taken from the substation GNN.

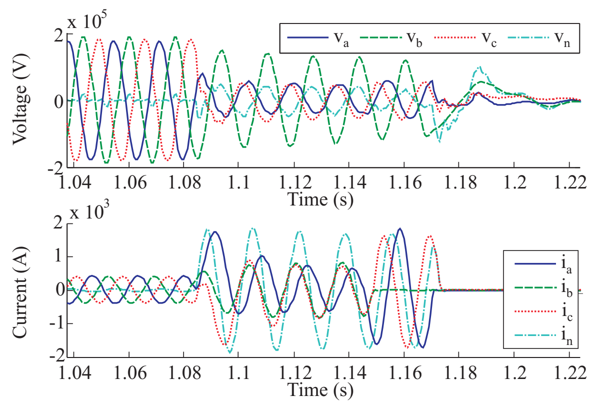

Fig. 15. Voltage and current records taken from the substation MRD.

TABLE III
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04F1 GNN-MRD.

Disturbance Data	**Substation GNN**		**Substation MRD**	
	PPAR	**DAPPE**	**PPAR**	**DAPPE**
Fault Type	ACG	ACG	ACG	ACG
Protection Tripping	Zone 1	Zone 1	Zone 1	Zone 1
CB Opening Time	65.00 ms	65.00 ms	200.0 ms	200.2 ms
Fault Location	12.9 km	12.8 km	46.5 km	42.1 km

Again, the disturbance information estimated by DAPPE was satisfactory. The estimated fault type and protection tripping were equal to those available in the PPAR. Also, the obtained values for the CB opening time and fault location were very similar to those reported by CHESF. It is important to point out that the fault analysis from the substation MRD was hampered by the CB opening in the substation GNN.

This led voltages and currents to present additional oscillations during the short-circuit, resulting in a difference between the estimated fault location and the one in PPAR of about 4.4 km. Even so, one can consider that DAPPE provided coherent reports regarding the fault diagnosis and protection performance, attesting its reliability.

3) Line 04L1 PRI-SBD: On April, 3, 2014, the transmission line 04L1 PRI-SBD was disconnected from the Brazilian power grid due to an AG fault, as explained in the PPAR made by CHESF. For the sake of space limitation, from now on, voltage and current records taken from the numerical distance relay installed at the analyzed lines are not presented. In Table IV, the obtained results using DAPPE are compared against those available in the PPAR.

TABLE IV
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04L1 PRI-SBD.

Substation SBD	**Disturbance Information**			
	Fault Type	Protection Tripping	CB Opening Time	Fault Location
PPAR	AG	Zone 1	71.67 ms	5.3 km
DAPPE	AG	Zone 1	66.62 ms	5.9 km

For this fault case, the protection tripping and the fault type were properly estimated. Also, the fault location and the CB opening time computed by DAPPE differ from those shown in the PPAR by 0.6 km and 5.05 ms only, respectively. By representing the CB opening time in number of power cycles, one can obtain identical results.

4) Line 04L3 STJ-FNL: According to CHESF's maintenance and operational crews, the line 04L3 STJ-FNL was disconnected from the power system on July 11, 2014, due to a CG short-circuit caused by the contact of the phase C with the vegetation in the area where the line passes through. DAPPE outputs and the data available in the respective PPAR are compared in Table V.

TABLE V
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04L3 STJ-FNL.

Substation FNL	**Disturbance Information**			
	Fault Type	Protection Tripping	CB Opening Time	Fault Location
PPAR	CG	Zone 1	58.33 ms	21.3 km
DAPPE	CG	Zone 1	59.68 ms	27.5 km

In this case, the fault was well-established since its first cycles, making it easy to estimate the fault type and the protection tripping signals. The results were in accordance to those in the respective PPAR. The CB opening time and the fault location estimated by DAPPE were also very close to those values found in the PPAR, presenting differences of 1.35 ms and 6.2 km, respectively, which are within an acceptable range of values for disturbance diagnosis purposes.

5) Line 04S1 TSA-PRI: On March 8, 2014, during a heavy rain, an ACG fault occurred in the line 04S3 PAF-CCD due to a lightning strike, as described in the respective PPAR. In Table VI, the comparison between the disturbance information estimated via DAPPE and those in the PPAR is presented.

As in the previous cases, DAPPE properly estimated the fault type and protection tripping, detecting the short-circuit into the zone 1 as expected. Also, the estimated values of both CB opening time and fault location presented small differences from those found in the PPAR, presenting differences of about 0.6 ms and 1.2 km only, respectively.

TABLE VI
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04S1 TSA-PRI.

Substation PRI	**Disturbance Information**			
	Fault Type	Protection Tripping	CB Opening Time	Fault Location
PPAR	ACG	Zone 1	61.67 ms	24.9 km
DAPPE	ACG	Zone 1	61.10 ms	26.1 km

6) Line 04M5 CTG-CMD: As reported by CHESF's maintenance and operational crews, on May 1, 2014, the transmission line 04M5 CTG-CMD was disconnected from the power system due to a CG fault caused by a shield wire which broke and fell down on phase C conductor. Table VII shows the comparison between DAPPE outputs and the disturbance data found in the respective PPAR.

TABLE VII
ANALYSIS OF THE FAULT OCCURRED IN THE LINE 04M5 CTG-CMD.

Substation CTG	**Disturbance Information**			
	Fault Type	Protection Tripping	CB Opening Time	Fault Location
PPAR	CG	Zone 1	66.67 ms	13.2 km
DAPPE	CG	Zone 1	65.93 ms	13.9 km

For this case, the results obtained by DAPPE were again very similar to those found in the PPAR. The fault type and protection tripping information were properly estimated, and both CB opening time and fault location values presented small differences, which were of about 0.74 ms and 0.6 km only, respectively. Therefore, from the evaluation of simulated and actual records shown in this paper, one can conclude that the first module of DAPPE is reliable and able to provide a good starting point to protection engineers during disturbance diagnosis and protection performance evaluation procedures, which are needed for the preparation of PPARs.

In future works, it is intended to improve the routines, reducing differences between the algorithms in DAPPE and those in the evaluated relays. Besides, new two-terminal fault location algorithms and other protection functions will be included in DAPPE, such as overcurrent, differential and teleprotection functions, resulting in more reliable and detailed disturbance and protection performance evaluation reports.

IV. Conclusions

In this paper, the evaluation of a software which is being developed by the São Francisco's Hydroelectric Company (CHESF) in partnership with Federal University of Campina Grande and researchers from other Brazilian institutions for disturbance diagnosis and protection performance analysis was presented. The software was named DAPPE (Disturbance Analysis and Protection Performance Evaluation).

The main goal is to create a computer program able to automatically generate reliable sketches of the Protection Performance Analysis Report (PPAR) that must be sent to Brazilian regulatory agencies after the occurrence of short-circuits in transmission lines. These reports contain information about the fault, such as fault type and fault location, as well as regarding the protection tripping process, such as the CB opening time and the distance protection behavior.

DAPPE's main objective is to reproduce the algorithms embedded into numerical relays, as close as possible. Thus, it estimates basic information that should be used in PPARs and then compares it with tripping signals available in fault records taken from the relays installed in the faulty line. DAPPE's first module evaluated in this paper has algorithms for phasor estimation, fault detection, fault classification, fault location, CB opening detection, CB opening time estimation and distance protection functions, such as the self-polarized and polarized mho and quadrilateral elements. The DAPPE output is a report, in which the main features of the fault and basic information about the protection performance are found.

The evaluation of DAPPE was performed in two parts. In the first one, fault records simulated in ATP were imported by CAPE, generating tripping signals. CAPE was chosen for this analysis because it has models of actual relays, which are supplied by the manufacturers themselves. Also, by using ATP fault records as inputs of DAPPE, the disturbance diagnosis and protection performance were estimated and, then, compared against the tripping signals obtained from CAPE. It allowed the evaluation of DAPPE performance considering more adverse cases for which there are no actual records available. In the second evaluation part, DAPPE was tested considering several actual fault records provided by CHESF. Basically, DAPPE outputs were compared with the information in the PPARs of each disturbance, generating the disturbance diagnosis and protection performance reports.

From the obtained results, one can conclude that DAPPE is reliable, as it provided information quite similar to those found in the PPARs, properly detecting cases in which relays were incorrectly set. Some improvements for DAPPE and additional analysis were also proposed in order to make the software more robust. Even so, for both simulated and actual case studies, the obtained results were considered satisfactory for the application in which DAPPE will be used in CHESF, demonstrating its usefulness and reliability.

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