A Procedure to Automate the Assessment of Generator Protection

Jonas Pesente, Miguel Moreto, Rodrigo Andrade Ramos and Renzo Fabián Espinoza

***Abstract*—The evaluation of protection performance after a generator shutdown is mandatory to assess if all automatic actions resulted in system security and safety to its users. Nowadays, however, the number of digital fault recorders and protection devices with oscillographic functionalities has intensely increased, making traditional manual analysis excessively time consuming. In this context, the contribution of this work is to propose a procedure to automate the evaluation of generating units' protection, making it possible for the engineers to focus on the most important data. The proposed procedure was evaluated through the development of a prototype designed using the multi-agent paradigm, taking advantage of its main computational benefits. The implemented prototype generated correct assessments for a large set of real disturbances, proving to be a very efficient and accurate tool for assessment and decision support to operators.**

***Keywords*—Disturbance Analysis, Power System Protection, Multi-Agent Systems.**

I. Introduction

PROTECTION of power system generators plays a key role in power system reliability since its misoperation may lead to major damages resulting in large repair costs [1], [2], also frequently being the root cause of the propagation of disturbances which may result in the occurrence of wide area shutdowns [3]. Furthermore, in the case of large disturbances, a significant number of trips are recorded, and due to the complexity of the protection systems of generators, a considerable amount of data is produced [4]. This large amount of data hinders disturbance analysis resulting in a time consuming task for engineers. This problem revealed the need of the development and deployment of unified frameworks for digital record processing, including automatic protection analysis [5].

In [6] an application of intelligent systems for the interpretation of alarms related to transmission protection showed that useful information for operators can be obtained by the proposed system.

A pioneer work of the application of the multi-agent paradigm in power system was presented in [7], proposing a conceptual structure for fault diagnosis and protection assessment of transmission systems. The protection assessment module of [7] is detailed in [8], where a fundamental basis, a software model and applications of transmission system protection evaluations are presented. In [9], an extension of this work and main conclusions gathered from the experience of the system operation are presented, and in [10] the work of applying this experience for establishing the requirements for an industrial system is discussed.

More recently, a detailed model for transmission system protection performance evaluation was presented in [11], showing the effectiveness of using detailed models in the automatic protection assessment.

All of these papers studied the problem of automating the evaluation of transmission system protection. In an attempt to fill the gap of research on protection assessment of bulk power system generators, this work presents a general procedure for the development of frameworks for this purpose, based on a detailed model of typical generator protection systems.

This paper is divided into the following sections: Section II shows the guidelines for the proposed Multi-Agent System (MAS); in Section III, a brief description of the generator protection systems and its protection functions are presented. In Section IV the tests performed for a set of disturbance cases are described and their results are evaluated; and Section V contains concluding remarks and future research directions.

II. Proposed Disturbance Analysis Multi-Agent System

In this work, the software design considered the architecture known as *belief-desire-intention*, which emphasizes the goal behavior of agents, an important feature for multi-agent programming [12]. The general operation of this system is determined by three guidelines:

1) *The software operation should be focused on equipment shutdowns*. As shown in Fig. 1 [13], equipment agents supervise the disturbance records and classify them cyclically. When a shutdown is identified, records from the overall oscillography network are recovered for a preset period. Once this period is finished, the system triggers actions such as processing the sequence of events, for example. After that, the inferred facts are communicated from the level of protection agents to the level of area agents, where the disturbance synthesis is written. This flow of actions results in the a trade-off between the amounts of processed data and the retrieved information from a specific disturbance.

2) *The actions of the agents must be coded as artifacts in the environment*. The usually proposed MAS considers

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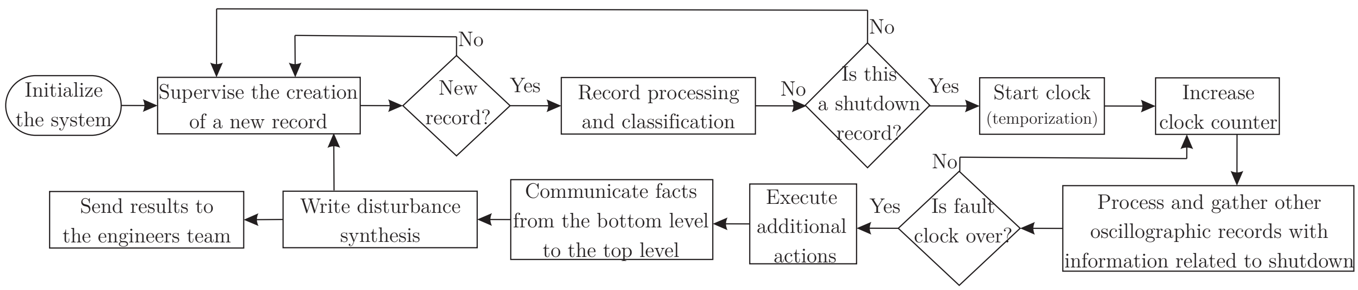

Fig. 1. Flow chart of the proposed disturbance analysis scheme, implemented using agent programming paradigm.

a manager/provider service scheme, in which agents encapsulate the code of their actions. In the proposed scheme, services must be deployed in a different dimension, as features. This ensures that the services will be executed in an exclusive thread, managed by the agent. Also, the organization is coded in a different dimension, which allows the reconfiguration of the system structure and the relations between agents by modifying organization layer. Executing the record processing in parallel threads reduces significantly the delay on retrieving disturbance information, presenting, for instance, a reduction from an hour to 3min in processing records from 10 sources in a single thread when compared to one thread per source, in the experiment described in [13]. The capacity of managing threads also allow the agents to prioritize records, avoiding cumulative processing delays to decrease software efficiency.

3) *The agents must be organized in the classes of protection, equipment, installation and area levels*. This way, each agent produces conclusions compatible with the characteristics of the available data, and the multi-agent system manages the processing of the data required in each stage of the execution.

The model of protective functions and the logic used to evaluate its performance are described in the next section.

III. Evaluation of the Protection Functions of Synchronous Generators

This section presents a survey of the techniques used for the evaluation of the correct actuation of the protection functions of synchronous generators. Based on this survey, justifications for the choices of the techniques used in this work are provided.

A. Protection of Synchronous Generators

A typical scheme of the protection functions for synchronous generators is presented in Fig. 2, which is in compliance with [14]. In Fig. 2, the numbers correspond to the ANSI code of the function, which can be grouped by the nature of the damage that synchronous generators are exposed to. In this work, the protection models presented are those involved in the case studies are described in Section IV. The

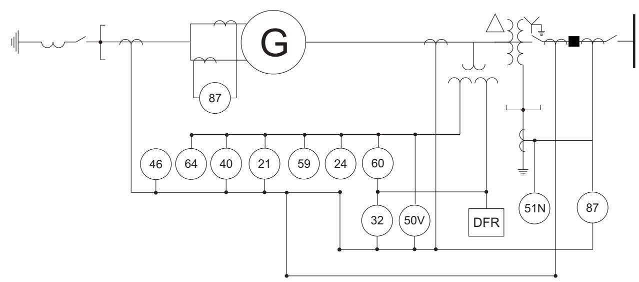

Fig. 2. General scheme protection of synchronous generators.

application of the protection models to electrical quantities for protection evaluation is performed after the execution of the classification of the records, described as follows.

B. Classification of Oscillographic Records of Synchronous Generators

There are two main types of oscillographic records: short term ones (generally waveforms), and long term ones (generally phasorial quantities). The level of detail of short term records made them more suitable for evaluation of protection actuation.

As previously metioned, several papers presented routines for oscillography classification, mainly applied to transmission lines monitoring systems [15]–[18]. It is also know that in large datasets of typical power plants, an amount as high as $99.8\,\%$ of total records do not contain fault information [13].

In this work, the method for classification of generator oscillography presented in [19] is used as a starting point for the proposal of a new approach. This new method is based on the use of phasor quantities applied to rules defined based on fault characteristics, improving significantly the fault identification accuracy.

C. Models of the Protection Functions of Synchronous Generators

In this work, the proposed method for the evaluation of the protection system actuation is based on the comparison between the *recorded events* and the *expected sequence of events*, which is determined by simulating the protection actuation using the recorded quantities. This concept is illustrated in Fig. 3.

Each of the stages presented in Fig. 3 considers a respective tolerance, which was defined in Section IV from

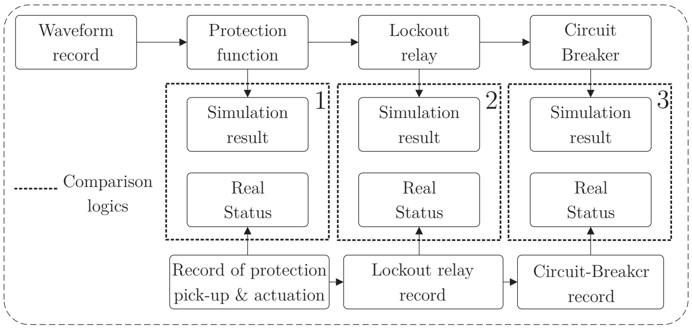

Fig. 3. Diagram of actions performed in protection actuation assessment.

the experience obtained with the relays actuations of the Itaipu power-plant generators over more than 35 years. The evaluation considers admissible the variations in protection time actuations of $\pm 17.5\,\%$ for time delayed functions, $\pm 15.5\,\mathrm{ms}$ for instantaneous protection, $30\,\mathrm{ms} \pm 28\,\mathrm{ms}$ for relay lockout and $47\,\mathrm{ms} \pm 27\,\mathrm{ms}$ for circuit breakers operation. Naturally, these tolerances can be calibrated for applications involving different power plants.

Although all the protection functions models presented in Fig. 2 were used to determine the expected protection actuation time for the prototype tests in this work, corresponding to box 1 in Fig. 3, the most significant are described as follows.

1) Current Differential (87) Protection: This function uses the current of two measurement points, protecting the inner region by means of the difference of the "input" and the "output" currents.

Typically, a characteristic between the difference (differential) and the sum (restraining) of these two currents minimizes incorrect actuations that can be caused by Current Transformer (CT) errors, and by the saturations of CTs which may occur due to high fault current values.

Although this model is very simple to be implemented, Digital Fault Recorder (DFR) usually records only the terminal current of the generator. This shortcoming can be overcome using records of other generators in the proximity: when a short circuit occurs inside the protection region of a generator, the phase of the current of the faulted generator tends to oppose to the phases of the currents of the remaining generators. In this work, an absolute angle difference higher than $165°$ was used to determine a fault inside the region of a specific generator that was shut down.

2) Protection against loss of excitation (40): This function identifies the condition of field excitation loss based on the impedance value measured from the generator terminals, because this value reaches certain non-operating regions in the R-X plane only when the generator experiences an under excitation condition.

There are three main methods to protect synchronous generators using this concept. The first method, also called the *Mason Method* [20], is defined by a circle with a diameter equal to X_d moved below the abscissa axis for an offset of $X_d^{'}$. The second, used for generators with $X_d > 1$ pu, known as the *method of Berdy* [21], includes a second circle of radius equal to 1 pu with the purpose of improving the selectivity of first method in the case of stable power oscillations.

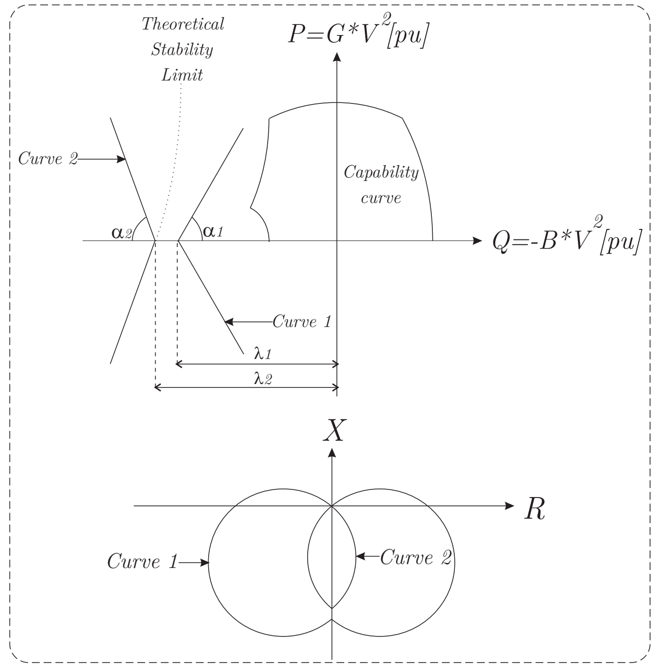

Fig. 4. Area of operation of the field excitation protection.

The third method is suitable for improving selectivity of the method of Mason for generators with $X_d < 1$ pu by using two of the circles of first method moved aside, composing an outer region when a single characteristic is active and an inner region when the two characteristics are active. This method, used in this work, is usually adjusted in the P-Q plane rather than R-X plane, by coordinating the first region with the under-excitation limiter of the generator, and the second region with the theoretical stability limit of the generator, as illustrated in Fig. 4.

3) Ground-Fault (64) Protection: There are three main schemes for ground-fault protection: 1) based on the measurement of 3^{rd} harmonic; 2) based in the injection of subharmonic content; and 3) based on residual voltage. Only the latter can be evaluated having information only about the generator terminal quantities.

In scheme 3, when a fault occurs, the faulted phase tends to ground potential. Thus, there is a residual voltage increase from near zero in normal operation to 1.73 of the rated voltage for one phase in fault conditions. This feature is used to identify a ground fault at the terminal of synchronous generators.

IV. Prototype Tests and Results

In order to test the proposed MAS system, a prototype was deployed at Itaipu power plant, which has 20 generators rated at $18\,\mathrm{kV}$ and $700\,\mathrm{MW}$ each, with protection settings presented in Table I, where V_n and I_n are the nominal voltage and current and V_r is the residual voltage of the generator, respectively.

TABLE I

SETTING FOR GENERATION PROTECTION.

Function	Pick-up value	Delay, T.Dial or Slope [s]
87	$0.1.I_n$	0.25
21-50V	$1.3.I_n$,$0,7.V_n$	2
40 Z1	λ_1 = -1.3, α_1 = 60^o	2
40 Z2	λ_2 = -1.4, α_2 = 70^o	0.2
60	$0.2.V_n$	0.5
46	$0.1.I_n$	30
64	$0.1.V_r$	0.5
59T	$1.2.V_n$	5
51N	0.8p.u.	0.4
24	1.2 pu, 142 s or 1.15 pu, 456 s or 1.1 pu, 1200 s	

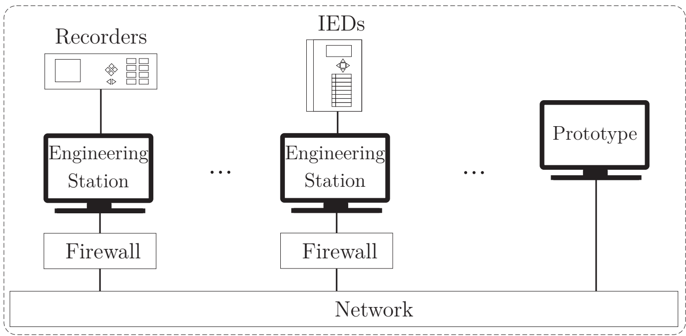

Fig. 5. Prototype Architecture.

The prototype developed considers the device structure available at the Itaipu power-plant, summarized as a connection of the primary devices to their engineering stations. The data can be retrieved through an existing network, resulting in the system architecture presented in Fig. 5. The system, however, can be expanded to multi-generator analysis.

The following subsections present the results produced by the prototype.

A. Evaluation of protection models based on fault simulations

The models presented in section III were implemented in the Alternative Transients Program version of Electromagnetic Transients Program (EMTP-ATP) [22], tripping generators whenever a fault simulation activates any protection function. The result of the quantities simulated were then used to generate COMTRADE files with the same ordering of the channels of the DFR, and then provided to the prototype processing.

1) Simulation of Loss of Excitation: A simulation of a field circuit breaker opening of an Itaipu generator produced the **P** and **Q** trajectories presented in Fig. 6, where the generator capability curve, the loss-of-excitation adjustments, and protections pick-ups and actuations are also shown.

The results produced by the prototype are synthesized in Table II, where a maximum difference of 13ms in the determination of all events can be observed, showing the effectiveness of the prototype.

Similar experiments were performed for all the other models implemented, presenting a maximum difference of 16ms, which further demonstrates the good accuracy of pick-up

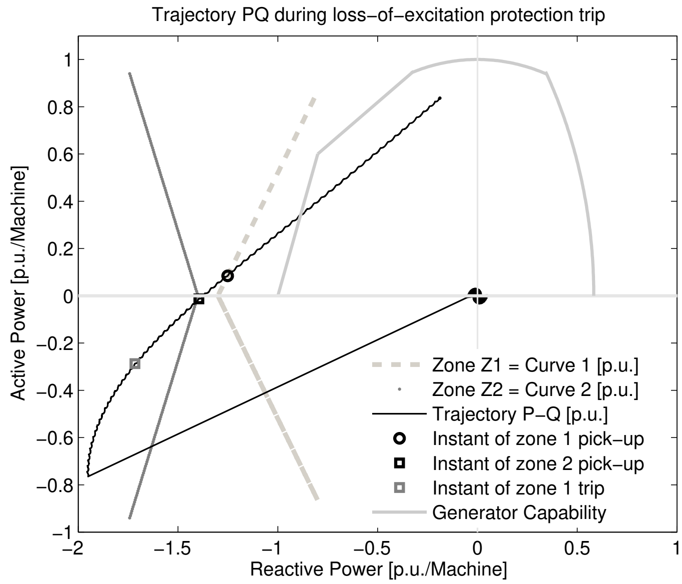

Fig. 6. PQ trajectory during actuation of loss of excitation protection.

TABLE II

COMPARISON OF EVENTS SIMULATED AND ASSESSED.

Event	Time in sim. [s]	Time in MAS [s]
Loss of field	0.100	-
Pick-up 1 of ANSI 40	0.5687	0.5692
Pick-up 2 of ANSI 40	0.6426	0.6430
Actuation 1 of ANSI 40	-	-
Actuation 2 of ANSI 40	0.8426	0.8431
Lockout relay state	0.8690	0.8690
Breaker opening	0.8750	0.8763

TABLE III

EVENTS ASSESSED BY THE PROTOTYPE FOR 64 ACTUATION.

Event	Time in MAS [s]	Assessment
Pick-up of Protection 64	0.625	Correct
Actuation of Protection 64	1.125	Correct
Lockout relay actuation	1.183	Correct
Circuit Breaker opening	1.214	Correct

and actuation determination by the routines deployed in the prototype.

B. Shutdown of a generator by ground protection actuation

In a report by Brazil′s National System Operator (ONS) it was described that in 02/23/2010, 4h8m AM, the automatic shutdown of generator 13 after an ground fault caused by fire in phase B of the unit transformer happened. The prototype correctly identified the shutdown and produced the assessment shown in Table III.

The Fig. 7 presents the voltage records processed by the software, where it is possible to verify that the residual voltage remains above the pick-up value of ground fault protection longer than the 0.5 seconds presented in Table I, indicating the correct protection assessment by the prototype.

Furthermore, in Fig. 7 the voltage of phase B tends to ground potential, indicating that this phase was the faulted one. A total of 486 MW of generation was lost due to this shutdown.

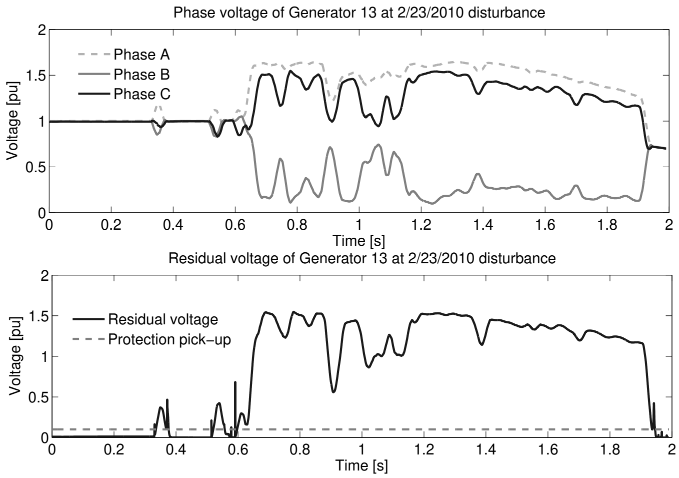

Fig. 7. Generator residual and phase voltages.

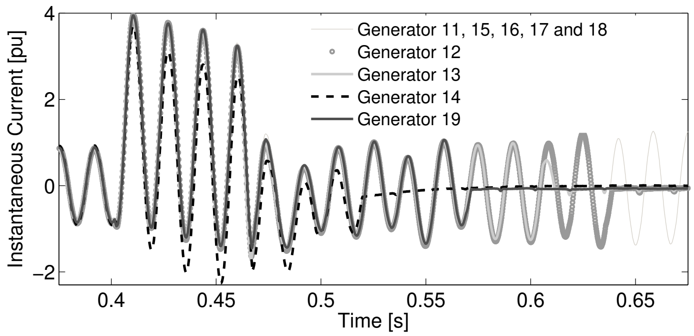

Fig. 8. Short-circuit currents of generators - 09/22/2015.

C. Short circuit of a busbar and shutdown of 4 generators

In a report by the ONS it was described that in 09/22/2015, 11h36m AM, an automatic shutdown of generators 12, 13, 14 and 19 togheter with busbar, ocurred after a disruptive discharge in Itaipu′s insulated gas substation. Generators 12, 13 and 14 were shut down by transformer temperature protection (49) and generator 19 by current differential protection. All of these protections actuated incorrectly (the only correct one was the busbar protection).

The prototype accurately identified the short-circuit and the four shutdowns illustrated by the current of the faulted phase in Fig. 8. The prototype also concluded by DFR processing that the shutdowns had been caused by incorrect current differential protection actuation.

The main events resulting of the prototype processing are presented in Table IV.

Later on, the conclusion that the actuation occurred in the temperature protection of the unit transformer for generators 12, 13 and 14 was determined by the processing of the sequence in event list, replacing the conclusion of the corresponding incorrect current differential protection actuation for the respective generators.

TABLE IV
RESULT OF PROCESSING OF RECORDS OF THE 09/22/2015 EVENT.

Event	Sequence of events in MAS
21 pick-up/gen. 12, 13, 14, 19	T_0 = 11:36:01.019
Gen. 19 lockout relay	T_0 + 66ms
Gen. 19 breaker opening	T_0 + 87ms
Gen. 12 lockout relay	T_0 + 125ms
Gen. 13 lockout relay	T_0 + 165ms
Gen. 12 breaker opening	T_0 + 165ms
Gen. 13 breaker opening	T_0 + 201ms
Gen. 14 lockout relay	T_0 + 245ms
Gen. 14 breaker opening	T_0 + 289ms

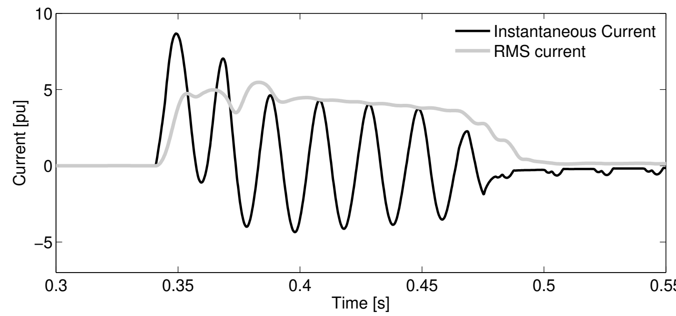

Fig. 9. Short Circuit current for generator 9.

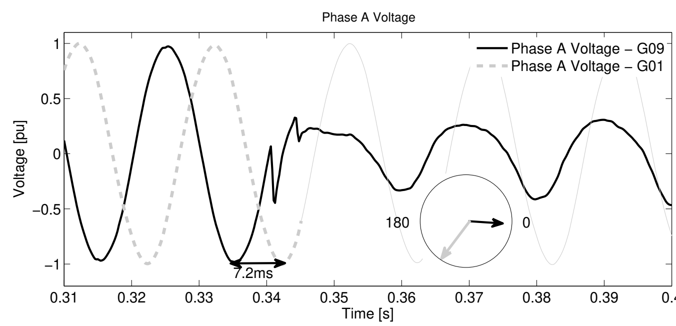

Fig. 10. Phase difference between system and unit U09 voltages.

D. Circuit breaker closing with generator in an asynchronous condition

In a report by the ONS it was described that in 08/30/2014, 4h32m AM, the automatic shutdown of generator 9 of Itaipu occurred, showing to the operators a set of features that pointed to the actuation of transformer neutral current differential.

The prototype identified the shutdown and pointed to the occurrence of a three-phase short-circuit in the generator, which reached its maximum rms value of 5.47 pu and its maximum instantaneous current of 8.76 pu, in phase *a*, as shown in Fig. 9.

The disturbance analysis concluded that, at the instant of circuit breaker closing, its terminal voltage leading the system voltage by 130°, as presented in Fig. 10, where the system voltage is compared to the voltage of the generator 1. This disturbance was the result of a failure in the logic functions that prevents circuit breaker operation in that specific condition. The prototype did not identify the residual differential protection actuation, since there was a negligible difference between the recorded transformer neutral and the sum of terminal currents.

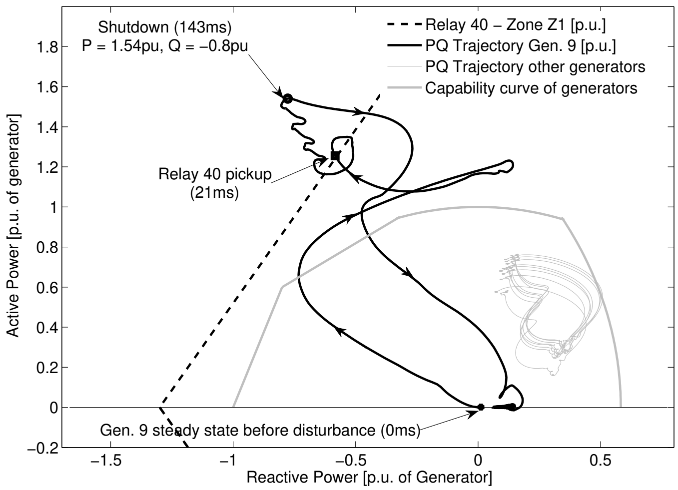

Fig. 11. Power of the generators during the disturbance of Aug. 30^{th}, 2014.

Simulations performed in EMTP-ATP demonstrated that the level of current recorded could have caused phase CT saturation, which lead to the conclusion that this was the cause of differential protection actuation. This case showed that further developments are needed for the inclusion of detailed CT and PT models in the prototype.

The prototype also showed that this event caused intense variations of active and reactive power for generator 9, which reached a maximum of 1.74 pu of apparent power ($(1.54 - \mathrm{j}0.8)$ pu), submitting the generator to a condition outside its capability curve as illustrated in Fig. 11.

The variation of power in generator 9 was compensated by significant variations of power in the other eight synchronized generators, as illustrated in Fig. 11. This reduced the systemic impact of the event (the local frequency reached a maximum of $50.27\,\mathrm{Hz}$).

V. Concluding Remarks and Future Work

Although little research has been published, protection assessment of generators clearly demands automatic pre-processing, which may avoids unnecessary manual efforts and also to alert engineers of incipient patterns in the equipment disconnections. This issue is a central matter in the case of large disturbance analysis, due the large amount of data produced in these particular events. Specially in these cases, automatic generator dynamic analysis is also a valuable tool helping engineers.

In this paper, a general scheme for the assessment of protection of generators is presented. It is based in the comparison of recorded actuations to the result of simulated actuations produced using recorded quantities over the detailed models of protection functions.

Real disturbances of ground-faulted generator, terminal short-circuit, circuit breaker closing in asynchronous conditions demonstrated the method efficiency and the accuracy of protection models. A case showing the importance of the inclusion of current transformer modeling was also presented, which will be incorporated in future work.

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References

[1] C. V. Maughan, "Incapability of analog relay protection to detect generator stator winding ground failures at neutral end," in *Electrical Insulation Conference (EIC), 2013 IEEE*. IEEE, 2013, pp. 490–493.

[2] A. P. Kharel, R. J. Rusch, and R. Thornton-Jones, "Review of generation system overflux limiters and protection and consequences of incorrect settings," in *IEEE PESGM*, 2010, pp. 1–6.

[3] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, , P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca *et al.*, "Causes of the 2003 major grid blackouts in north america and europe, and recommended means to improve system dynamic performance," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1922–1928, 2005.

[4] C. J. Mozina, "Coordinating generator protection with transmission protection and generator control nerc standards and pending requirements," in *Protective Relay Engineers, 2010 63rd Annual Conference for*. IEEE, 2010, pp. 1–12.

[5] J. E. Dagle, "Data management issues associated with the august 14, 2003 blackout investigation," in *IEEE PESGM*, 2004, pp. 1680–1684.

[6] J. R. McDonald, G. M. Burt, and D. J. Young, "Alarm processing and fault diagnosis using knowledge based systems for transmission and distribution network control," in *IEEE T&D*. IEEE, 1991, pp. 280–286.

[7] J. A. Hossack, J. Menal, S. D. McArthur, and J. R. McDonald, "A multiagent architecture for protection engineering diagnostic assistance," *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 639–647, 2003.

[8] E. Davidson, S. McArthur, and J. McDonald, "A toolset for applying model-based reasoning techniques to diagnostics for power systems protection," *IEEE Transactions on P.S.*, vol. 18, pp. 680–687, 2003.

[9] E. M. Davidson, S. D. McArthur, J. R. McDonald, T. Cumming, and I. Watt, "Applying multi-agent system technology in practice: Automated management and analysis of scada and digital fault recorder data," *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 559–567, 2006.

[10] G. Napier, E. Davidson, S. McArthur, and J. McDonald, "An automated fault analysis system for sp energy networks: Requirements, design and implementation," in *IEEE PESGM*, 2009, pp. 1–7.

[11] F. Lopes, D. Barros, R. Reis, C. Costa, J. Nascimento, N. Brito, W. Neves, and S. Moraes, "Disturbance analysis and protection performance evaluation," in *IEEE IPST*, 2015.

[12] D. Issicaba, "Block-oriented agent-based architecture to support the power distribution system operation: System design and environment model," Ph.D. dissertation, University of Porto, 2013.

[13] J. Pesente, G. Herbig, M. Moreto, and R. A. Ramos, "A belief–desire–intention multi-agent architecture for efficient power plant disturbance analysis," *JCAES*, pp. 1–10, 2018.

[14] I. P. S. R. Committee *et al.*, "Ieee guide for ac generator protection," *IEEE Std. C*, vol. 37, pp. 1–177.

[15] A. Gaouda, S. Kanoun, M. Salama, and A. Chikhani, "Wavelet-based signal processing for disturbance classification and measurement," *IEEE T&D*, vol. 149, no. 3, pp. 310–318, 2002.

[16] M. Kezunovic, P. Spasojevic, C. Fromen, and D. Sevcik, "An expert system for transmission substation event analysis," *IEEE Transactions on Power Delivery*, vol. 8, no. 4, pp. 1942–1949, 1993.

[17] A. Pradhan, A. Routray, S. Pati, and D. Pradhan, "Wavelet fuzzy combined approach for fault classification of a series-compensated transmission line," *IEEE Transactions on Power Delivery*, vol. 19, no. 4, pp. 1612–1618, 2004.

[18] F. Lopes, D. Barros, R. Reis, C. Costa, J. Nascimento, N. Brito, W. L. Neves, and S. Moraes, "Methodology for protection performance evaluation on power transmission networks," *IEEE Transactions on Power Delivery*, 2017.

[19] M. Moreto and J. G. Rolim, "Using phasor data records and sequence of events to automate the classification of disturbances of power generating units," *EPSR*, vol. 81, no. 7, pp. 1266–1273, 2011.

[20] C. Mason, "A new loss-of-excitation relay for synchronous generators," *Transactions of the AIEE*, vol. 68, no. 2, pp. 1240–1245, 1949.

[21] J. Berdy, "Loss of excitation protection for modern synchronous generators," *IEEE Transactions on Power Apparatus and systems*, vol. 94, no. 5, pp. 1457–1463, 1975.

[22] F. Mourinho, J. Pesente, R. Otto, and R. A. Ramos, "Modeling and evaluation of the protection of distributed synchronous generators connected to unbalanced systems," in *IEEE PESGM*, 2014, pp. 1–5.