Electrical Power and Energy Systems 32 (2010) 599–606

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Maintenance and operation of a hydroelectric unit of energy in a power system using virtual reality ☆

Marcos Paulo Alves de Sousa [a,b,*], Manoel Ribeiro Filho [a], Marcus Vinícius Alves Nunes [a], Andrey da Costa Lopes [a]

[a] *Federal University of Pará, Faculty of Engineering Computing, Augusto Correa Street, No. 1, Belém, Pará, Brazil*
[b] *Emílio Goeldi Museum, Service Data Processing Department, Perimetral Avenue No. 1901, Belém, Pará, Brazil*

ARTICLE INFO

Article history:
Received 12 September 2008
Received in revised form 23 June 2009
Accepted 10 November 2009

Keywords:
Virtual reality
Interactive training
Computational simulation
Hydroelectric unit of energy

ABSTRACT

This paper presents a new approach to training for hydroelectric unit of energy (HUE) by using virtual reality Non-immersive techniques. The software offers two modules of training: maintenance and operation. The first module, maintenance, uses the learning approach based on practice and offers different training levels, divided into three modes: automatic, guided, and exploratory, in which these modes are accessed according to the acquired degree of knowledge by the trainee in relation to maintenance procedures. The second module, allows the trainee to visualize the operation of HUE during a certain event as the electromechanical dynamics of the turbine-generator assemblage in the virtual world by the visualization of several requisite conditions before the startup-shutdown procedure of HUE.

1. Introduction

Currently, the training centers of engineering has invested in new technologies [1] that offer a better development of teams, with lower operational cost [2], without offering risks to people and environment.

The traditional training centers are still limited in the use of manuals and theoretical classes, and the process of acquiring knowledge depends on the opportunities of the day-to-day, without guarantees of full technical skills; for this reason, new technologies have been researched to improve the training level of specialized teams. One of them is virtual reality (VR) [3], which allows the trainee to easily manipulate the pieces that are difficult to visualize and access. In addition, VR helps to visualize assembly procedures that are not always predicted in manuals and provides the opportunity to simulate error situations with no impact on real production.

The importance of training in the maintenance and operation process of the hydroelectric unit of energy (HUE) equipments [4] can be underlined by the direct impact on the quality of energy generation and on the risk of operation. HUE is a continuous process of production, in which the hydraulic energy is converted into mechanical energy, and finally, into electrical energy. HUE is formed by three main components: pipeline, turbine, and generator [4], as shown in Fig. 1.

The present work proposes a training system for the maintenance of pieces contained in a HUE using Non-immersive VR techniques, attending to the main requisites of virtual training that are available in Refs. [5–10]. The training environment is comprised of the maintenance module, that corresponds to the training procedures for the maintenance of the sub-units of the HUE and the operation module.

Section 2 presents a contextualization of VR and its application in the training process for industrial maintenance. Section 3 shows the study proposition of the training system for maintenance of a HUE using Non-immersive VR techniques. Section 4 presents the modules related to maintenance and operation.

2. VR and its applications in the assembly and training for industrial maintenance

The increase in the complexity of technical equipments and machines demands a higher level of qualification from the employees in various industries. The increases in costs and efforts that are demanded of qualified technicians have made the training centers of the respective companies to search for new methods and tools to accomplish training with lower investments. There are additional reasons and demands that necessitate the use of innovative training techniques in the technical domain, such as the following [5]:

☆ This paper was written on the basis of studies carried out through a research project supported by M/s. ELETRONORTE (Centrais Elétricas do Norte do Brasil, S.A.).
* Corresponding author. Address: Federal University of Pará, Faculty of Engineering Computing, Augusto Correa Street, No. 1, Belém, Pará, Brazil. Tel.: +55 91 3274 3755.
E-mail address: msousa@museu-goeldi.br (M.P.A. de Sousa).

0142-0615/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2009.11.016

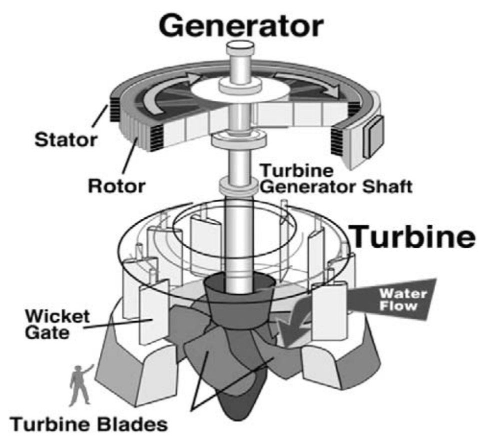

Fig. 1. Hydroelectric unit of energy (HUE).

- The necessity for a training system that can be integrated into the work environment;
- The necessity for a training offer that can be globally accessible based on the demand;
- The necessity for a flexible training that can be offered anywhere at any moment;
- The necessity for the integration of pedagogical aspects and human factors in the training environment that aids the final user in the achievement of the intended effects and results of learning.

According to studies by Boud et al. [6], the acquisition of abilities is divided into three stages:

- The cognitive stage, in which people learn the procedures and basic properties of the object;
- The associative stage, in which the procedures and knowledge about the objects function as part of the sequence of actions;
- The qualified stage, in which the sequence of actions are combined according to a specified standard of activities.

Each stage requires a decrease in the level of conscious control. One of the discussions in Boud's work is that the activities that are carried out by traditional methods are based on the cognitive stage, whereas VR leads the trainee to the other subsequent stages, thus offering the trainee superior stages of ability in relation to conventional training.

Another important study conducted by Waller et al. [11], referring to the retention of spatial ability for assembly tasks, concludes that the retention of the abilities of the trainee is higher when VR is used, in comparison with traditional means, especially when it involves a certain period of time after the training.

Over the preceding years, industrial maintenance and training have been the subjects in many studies that involve VR, because VR has a greater potential in the training sector by offering an approach in which the demands of training and the necessity mentioned above can be integrated in one single environment.

This potentiality of VR is motivated by the favorable experiences resulting from education in engineering [12], visualization of complex virtual environments in CAD [7,13], its usefulness in assembly processes [10,14], and applications of training based on the learning-by-doing approach [8,9,15,16]. This approach encompasses two vital elements: the personal experience made possible by simulation of the real-world environment of (using a graphic user interface or VR or both) and the training process initiated by following the guidance of the instructor.

During the researches into the subject, VR applications related to both immersive and Non-immersive training were observed. In spite of the fact that immersive application offers a high level of interactivity and realism, it nevertheless requires advanced hardware and software for its implementation, limiting its use in various applications and inhibiting its popularity. Moreover, the ergonomics of most nonconventional devices is still a great problem that prevents the use of immersive VR into a widely accepted tool among users and researchers [9].

Currently, there are good examples of Non-immersive applications related to industrial maintenance and assembly, such as V-realism [8] and visualization decision support system (VDSS) [16]. The first example is a system oriented toward objects, which imparts assembly training to specialized engineering teams, aiming to provide the maintenance engineers with a three-dimensional visualization and an effective simulation of disassembly sequences in the maintenance of equipments and workpieces. The second example is the visualization system of a hydroelectric generator unit, which allows an understanding of the physical structures and the monitoring condition for a diagnostic analysis of the HUE components.

3. Study of a HUE using Non-immersive VR techniques

As a case study, the HUE plant of the Tucurui hydroelectric plant was investigated. This plant is located in North Brazil, at 3 50′S latitude and 49 30′W longitude of Brazil over the Tocantins River in Pará State. The Tucurui plant has an installed potency of 8370 MW and has 23 HUEs. It is the second biggest Brazilian hydroelectric project and the fifth biggest in the entire world.

For implementation of the virtual environment of maintenance training for HUE, a tool called the virtual generator unit (VGU) was developed, based on Non-immersive VR techniques, which has three main modules: educative, maintenance and operation.

The previous version of the VGU contains educative module, which aims at the visualization and general study of the component sections of a HUE, which can be found in Ref. [17]. The current version offers new modules for the maintenance and operation, allowing visualization of procedures, and greater interactivity and navigability in virtual environment.

Maintenance module is a training based on learning-by-doing and it offers different levels of training and evaluation to the technicians.

Operation module allows the trainee to visualize the operation of the HUE during certain events as the electromechanical dynamics of the turbine-generator assemblage in the virtual world during the visualization of several requisite conditions before the startup-shutdown procedure of HUE. Modules exclusively designed to study the assembly, maintenance, and operation form the focus of this work.

For implementation of VGU, were used the DELPHI language and the components Open Source GLScene [20]. GLScene is an OpenGL based 3D library for Delphi. It provides visual components and objects allowing description and rendering of 3D scenes. The Hardware configuration used was a PC with processor Core 2 Duo E4500 and 2 GB of Memory RAM and graphics board NVIDIA GEFORCE 6500 (256 MB).

4. Modules on VGU system

Modules related to the maintenance and operation are the objects of study in this work, and they are detailed in the following topics.

4.1. Maintenance module

The training environment in VGU uses Non-immersive VR resources permitting the trainee to virtually carry out the maintenance procedures, working through the assembly and disassembly operations of the pieces and equipments of HUE, on the basis of the operation and maintenance manuals of the turbine provided by ELETRONORTE.

The VGU system offers two types of visualization for this maintenance step. The first is the external superior vision of the Cone, which allows the trainee to visualize the withdrawal of the lid of the cone floor from the outside, and, from the opening in the lid of the floor, the trainee can manipulate the pieces in the maintenance area.

Following the scheme of learning by steps, in accordance with the trainee's degree of knowledge, as contained in study by Bluemel [5], the module has three training modes: automatic, guided, and exploratory. These modes are accessed on the basis of the degree of knowledge of the trainee in relation to maintenance procedures.

4.1.1. Automatic maintenance mode

In this mode, an automatic animation of the steps in the maintenance procedure is presented as an orientation technique for the trainee. According to the type of maintenance chosen by the trainee, the animation is carried out, and the procedural instructions are shown in the text area. Interaction with the virtual environment is the least possible in this mode. The maintenance procedure is developed through an animation that shows the assembly and disassembly movements of the piece, and the trainee controls the entire process.

This training aims to present the pieces that are involved in the maintenance and to show the correct position of the technician in the HUE structure and the correct sequence in which the pieces must be manipulated. An animation example of the disassembly maintenance procedure of the superior trunnion plug is provided in Figs. 2a–2d.

Fig. 2a shows the beginning of the assembly procedure. In the bottom part of the text screen, the system asks the user to click on the "Animation" button to start the procedure, and the image in the center of the screen shows the removal of the eccentric pine (inside the vertical circle) and the screws from group A (inside the horizontal circle). The remaining consecutive steps of the maintenance procedure are shown in Figs. 2b–2d.

4.1.2. Guided-training mode

In this training mode, the system guides the user by commands that detail the maintenance procedures. In contrast to the automatic mode, here the trainee has to manually select the maintenance tasks using the mouse, which allows the selection and movement of pieces through picking events (virtual choice of objects by clicking on the mouse). When a piece, which is part of the maintenance context, is clicked on, a message informs the name of the object in the scene and, simultaneously, the instructions related to the object are shown in the text inferior area.

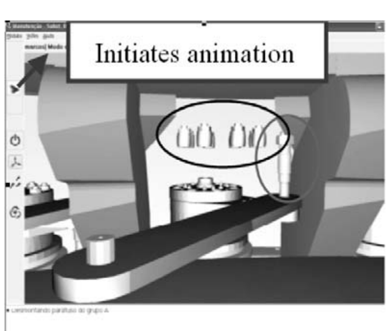

Fig. 2a. Beginning of maintenance animation of superior trunnion plugs.

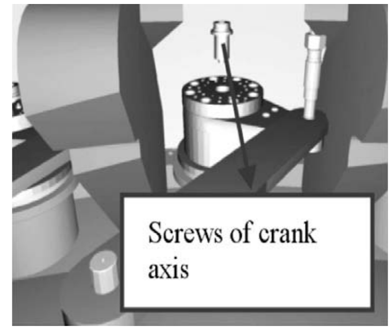

Fig. 2b. Removing the screw of crank axis.

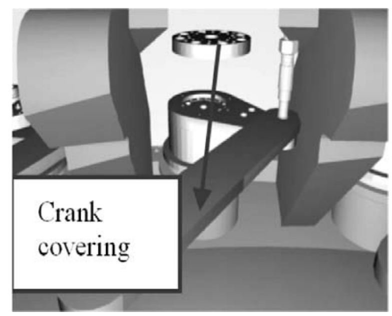

Fig. 2c. Removal of the crank covering.

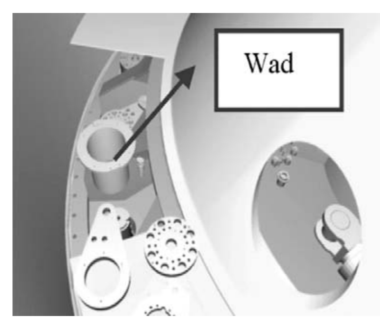

Fig. 2d. Removal of wad.

When a piece is moved in the correct sequence, a positive message is shown, informing that the piece was assembled or disassembled successfully. To convert the features of virtual pieces to reflect the real world, the collision-detection property is used, with the aim of preventing the user from mistakenly penetrating with one piece after another.

When the maintenance is completed, the evaluation result for the trainee is shown in the text area, and it contains information on the evaluated mode (1 – Automatic Mode, 2 – Guided Mode, and 3 – Exploratory Mode), the evaluated training (1 – replacement of superior-lid gasket and 2 – replacement of inferior-lid gasket). Moreover, the evaluation result shows the percentage of correct answers during the maintenance procedures. In case the training has been completed with no errors, the system makes available a button that enables the continuation to the next mode and a "restart" button for those cases where the trainee wants to repeat the task, as shown in Fig. 3.

4.1.3. Exploratory training mode

When this mode is begun, the learner is already familiar with the assembly and disassembly procedures and, from this moment

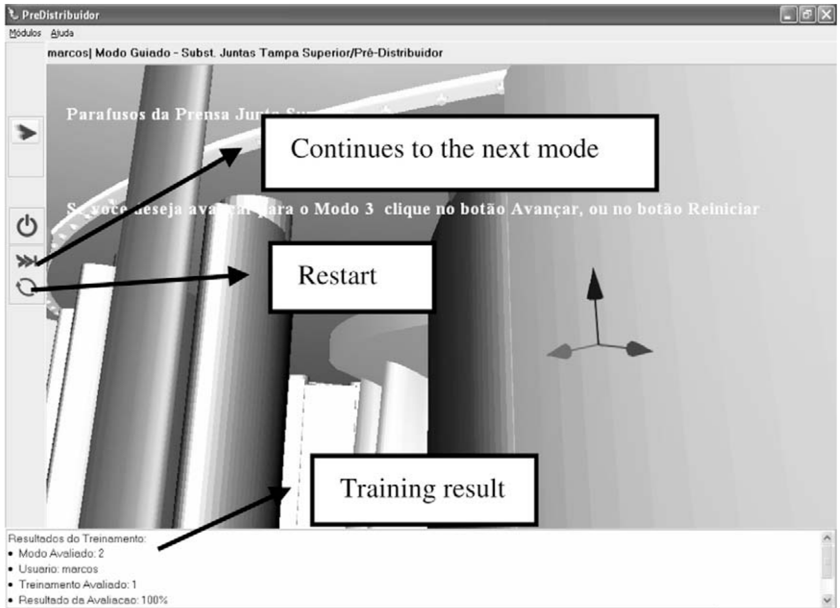

Fig. 3. Choice of continue and repeat buttons when the maintenance is done.

on, the trainee's knowledge is tested by performing tasks with no aid from the system. The trainee sequentially removes the screws, the press gasket, and the gasket and replaces them using the mouse. At the end of each correct step, the system shows a message in the virtual world indicating its accomplishment, which informs that the removal of the superior gasket has been concluded.

In the text area, no message is shown about the maintenance procedure; only the messages related to the correct or incorrect selection of pieces are shown. When the maintenance task in the exploratory mode is completed, the system informs that the training has successfully concluded and, thereafter, the trainee is able to learn a new procedure, because he has passed all the training modes related to the current procedure.

4.2. Operation module

The operation module allows the trainee to visualize the HUE operation during a certain event as the electromechanical dynamics of the turbine-generator assemblage in the virtual world. This module is divided into two main parts: contingencies and start-up-shutdown procedure. In the contingencies, the HUE is interlinked with the power system and the operator can observe the behavior of the system during load variations and faults in the electrical system as short circuits. In the startup-shutdown procedure of HUE, a virtual simulation is presented, in which the operator visualizes several requisite conditions necessary to turn off the HUE or interlink it to the power system.

4.2.1. Contingencies

The study of the dynamic behavior of a hydropower plant during contingencies is essential to the planning of expansion of an electrical power system. Without this knowledge, it is impossible to project the protection system for the generator and the grid and to plan the operation of the system, as described in the report by Kundur [18].

The main objective of this module is to contribute to the establishment of a relationship between the dynamic models of HUE operation with the VR environment, through visualization of the mechanical process of the turbine distributor.

In this module, it is possible to analyze the dynamic behavior of the turbine-generator assemblage in a HUE, operating in both the permanent and transitory states, which allows the visualization of a HUE linked to a power system and an animated vision of the operation of the hydropower plant.

By clicking on the "Turn button", as shown in Fig. 4a, HUE starts operation, detaching the animation of the rotating parts for the turbine-generator assemblage in the virtual world. The animation of the jointed parts of HUE is governed by the electromechanical dynamics of the turbine-generator assemblage and, according to the event simulated, a certain contingency can dynamically alter the values of the rotor speed as the mechanical torque, the opening of the distributor, and the terminal voltage, among others.

In the same sequence, by clicking on the "Apply Contingency" button, the application of a short-circuit is accomplished in the terminal of the HUE substation. By the application of this contingency, it is possible to verify the performance of the speed governor through the animation of the turbine-distributor system. For a Francis turbine, the control is exerted by an assemblage formed by the guide vane, servomotors, and regulation rings, collectively called the "distributor". Control is exercised by altering the position of the guide vane.

With the purpose of procuring a graphic visualization of the main electromechanical magnitudes of HUE during the operation, the Graphs interface (see Fig. 4b) has been developed. This interface is enabled by clicking on the Oscillographies button as shown in Fig. 4a.

The visualization of the process of short-circuit in a hydraulic generator, obtained with the help of the VR environment, helps the professional to understand the phenomenon, which corresponds to the acceleration process of the generator and the consequence of this acceleration to both the turbine and the electrical system as a whole.

Fig. 4b shows the behavior of the frequency of the turbine in a condition of short circuit. There is an acceleration of that and then the return to a steady condition. Such frequency is related with the speed of the generator rotor.

A single Francis turbine-generator, with the exciter and governor in a hydropower plant connected to the local load and infinite bus as shown in Fig. 5, is considered for the study. Although the ac-

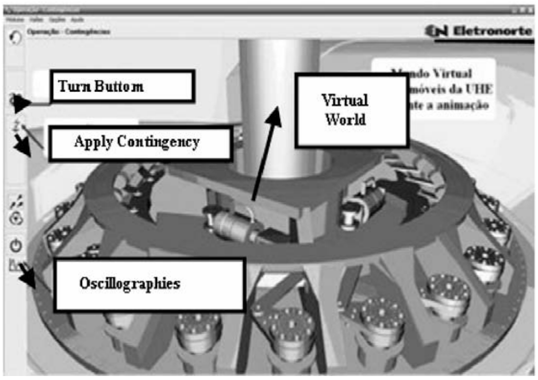

Fig. 4a. Initial interface of the operation.

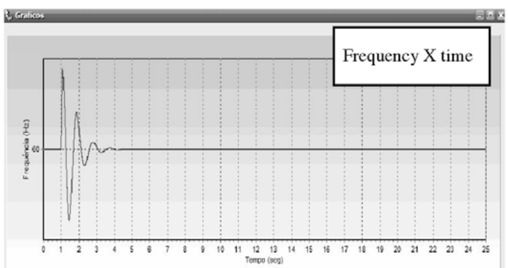

Fig. 4b. Graphs interface.

tual power network is more complex, the Single Machine Infinite Bus (SMIB) system is, however, a useful starting point for a study of its design and performance [4,18,19].

The block diagram in Fig. 6b represents the Excitation (Efd) Control System Equations block. Such system is responsible by the terminal voltage control of the generator. On the other hand, the block diagram in Fig. 6a represents the Turbine Governor Equation block from Fig. 5. That is responsible for the speed control (ω) of the generator rotor and position of the guide vane (G). Both are visible as an animation on the RV environment.

The electromechanical simulation of the plant is implemented using the models suggested to the turbine, speed governor, and excitation system by Kundur [18], according to Figs. 6a and 6b.

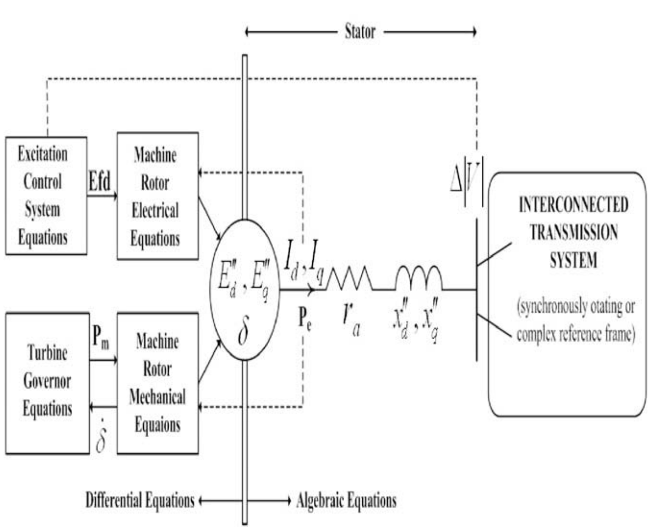

Fig. 5. A hydropower plant connected as SMIB system.

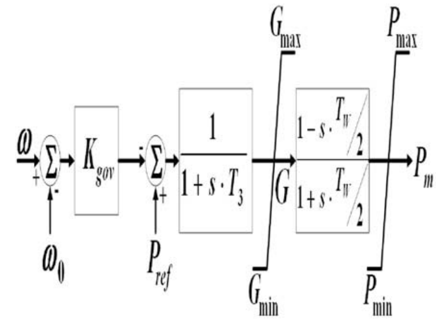

Fig. 6a. Speed Governor and Hydraulic Turbine Model.

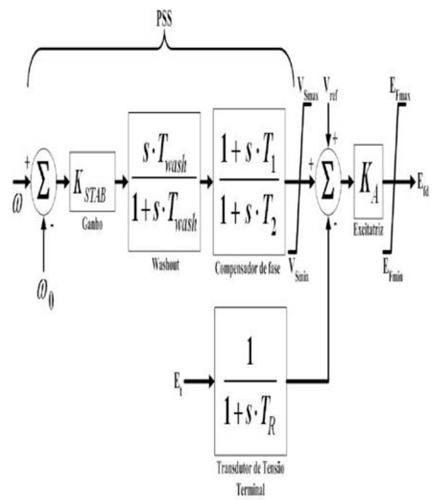

Fig. 6b. Fast Static Exciter and Power System Stabilizer Model.

The limits of the governors are determined such that the simulations become more realistic. The time constants and gains of the Speed Governor and Static Exciter Models were obtained from [18].

4.2.2. Startup-shutdown procedure

The knowledge of basic operations necessary for the startup, shutdown, and restart procedures is tested in this module.

In this mode, a single start command causes a sequence of activities in which the necessary auxiliaries are started, and the necessary safety checks are carried out at each stage of the sequence. All through the startup and shutdown procedures, textual details are delivered to the user in the screen of the virtual environment.

4.2.2.1. Automatic startup procedure. In the startup sequence, the machine is in the state of "Stopped Unit". After the startup command is given, the three-dimensional simulation of the startup commences, and a series of requisite conditions is verified automatically simultaneously: the open water-intake gate (Fig. 7a), the closed distributor (Fig. 7b), and the lowered generator rotor (Fig. 7c).

In Figs. 8a–8d, some of the requisite conditions of startup, necessary for the unit to be ready for the mechanical turn that causes the opening of the distributor are shown. This process begins the rotational movement of the machine, or in other words, the startup.

With the requisite conditions of mechanical turn being satisfied, the distributor is ready to open, and the machine enters into unloaded gear without excitation. At 80% of the rating speed, the requisite conditions for excitement are satisfied and the automatic

Fig. 7a. Open water-intake gate.

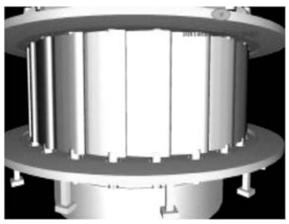

Fig. 7b. Closed distributor.

Fig. 7c. Lowered generator rotor.

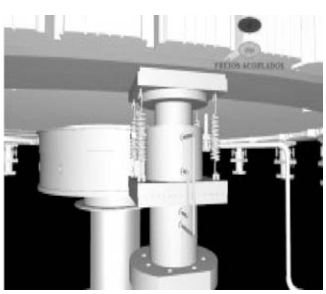

Fig. 8a. Coupled brakes.

Fig. 8b. Bomb turned on.

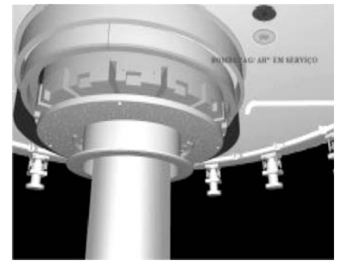

Fig. 8c. Oil injection in the sliding slippers of the machine thrust bearing.

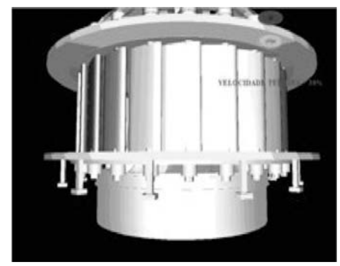

Fig. 8d. Open distributor.

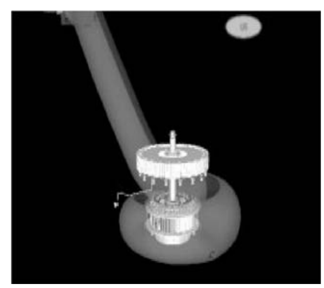

Fig. 9a. Synchronized machine.

Fig. 9b. Turbine rating speed smaller than 15%.

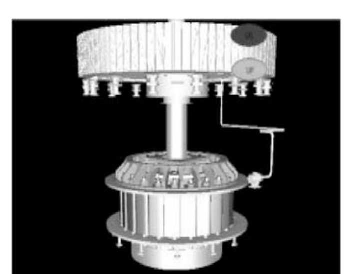

Fig. 9c. Stopped machine.

closing of the field circuit takes place; subsequently, the unit enters into excited unloaded gear. With the requisite conditions for synchronization satisfied, the main circuit breaker is closed. At 90% of the rating speed, the unit is synchronized, it turns into unload and, soon after, it begins to take load.

4.2.2.2. Automatic shutdown. In the stop sequence, the machine is in the synchronized state (Fig. 9a) after the order of "normal shutdown". The three-dimensional simulation of the shutdown begins with the following procedures and maneuvers: verification whether the machine is in active load and/or reactive load joint of the operation, reduction of the active and reactive load to zero, and, whether the main and field circuit breakers are open.

With this step, the closing of the guide vane is propelled until the opening reaches 0%. With the total closing of the guide vane, the slowing down of the assemblage begins from 100% and continues until null speed and the following events occur: at 30% of the rating speed, the brakes of the machine are coupled and the command for startup of the hydraulic bomb is given. With brakes being applied, the machine reduces the speed quickly until it stops (Fig. 9b).

After confirmation of the stopped status of the machine through the verification of the speed indicator as 0%, the hydraulic bomb is turned off (Fig. 9c), and later, the brakes are uncoupled and the unit is stopped (Fig. 9c). The machine in the stop condition, as described in this paper, is in the state of a normal stop, ready to be driven to the startup of the unit at any instant, for which it is enough to carry out the startup maneuvers.

5. Conclusions

This paper presents the conception and the experimentation with the VR system, a project aimed at training through modules to the assembly, maintenance and operation of HUE pieces. The system adopts a modular architecture, which makes it extensible and flexible.

The operation module in this system, allows the trainee to virtually carry out the real-time operational procedures of the HUE utility. The maintenance module uses the learning approach based on practice and offers different levels of training, divided into three modes: automatic, guided, and exploratory. These modes are accessed according to the acquired degree of knowledge of the trainee with reference to the maintenance and operational procedures. In this case, the combination of traditional evaluated learning programs with VR systems in the area of power system has been presented.

The assembly system offers the trainee a virtual visualization and training regarding piece-assembly procedures in general, and the maintenance module presents the maintenance procedures in a manner that can increasingly enhance the involvement of the trainee with the system. The main contribution of the operation module is the establishment of a relationship between the dynamic models of the HUE operation with the VR environment through the visualization of the mechanical processes related to the turbine distributor.

The application of virtual training proposed by Angelov [15] offer specific modules for simulation of real situations, using Research Module, and for learning step-by-step to understand components of the power engineering, through the Teaching/Training Module, in single level of learning. The VGU works similarly to the previous system, however, offers different training levels, according to the acquired degree of learning by the trainee.

In comparison with the system architecture proposed by Li [8], the VGU also contained training modules, representation of the virtual environment, and a graphic interface. Moreover, in addition to containing a piece-model repository in CAD, the VGU also possessed a repository of documents in XML format containing information regarding the models in CAD and the procedures of training.

When compared with the VDSS solution, proposed by Guo [16], the VGU tool offers a specific component for training and evaluation, in addition to the characteric three-dimensional visualization.

Considering the "help" properties of the virtual assembly process and disassembly simulation referred to in Sá's work [10], the VGU maintenance module has important features, such as training procedure involving the moving of virtual pieces based on real physics, in addition to containing collision-detection properties and an operation module.

The hydroelectric power plants use technical instructions of maintenance and operation to instruct maintainers and operators about the maintenance and operation procedures to be executed in their generating units. These instructions consist of well defined scripts with 2D flat drawings and of activities in textual format. The available instructions of maintenance at the hydroelectric power plant are called Technical Instructions of Maintenance or TIM. They consist of well defined scripts with 2D drawings and activities in textual format. This material does not help too much the understanding of the technicians in charge for disassembly and assembly procedure of the equipments. The Technical Instructions of Operation, TIO, also consist of texts written in paper and have the same problems as the TIM, therefore, it impels in the operators' understanding about the effects on the equipments, caused by its direct action during a maneuver. This paper presented a system which allows a technician to create a technical instruction inside a virtual environment, called Virtual Technical Instruction (VTI), of operation or maintenance. This is a new contribution of this paper, as compared with previous workers.

The first version of the prototype has been implemented in the hydroelectric power plant of Tucurui – ELETRONORTE (Concessionary of Electrical Energy of North Brazil) located in the state of Pará, in the north of Brazil, for presenting the software and providing initial training to electrical engineers and operators. Technical instructions of maintenance and operation have been tested in HUE by technical staff, and it has been unanimously accepted.

The achieved result was a greater dependability on interventions by maintenance and operation technicians, as well as an improvement of intellectual capital and manageable training. We could obtain a practical feedback of installation maintainers and operators regarding easiness and didactics of users into virtual space, by means of training of its applications when visualizing, manipulating and exploring virtual data and objects (with real world interaction). These data and objects represent real data and objects which are manipulated by technicians in their schedule. Thus, they are able to promote improvement actions and solutions, which are able to increase generation availability and to maximize the results that are defined according to the practice and standard of excellence at work defined by the company.

References

[1] Agostini M, Decker I, Silva A. A new approach for the design of electric power system software using object oriented modeling. Int J Electr Power Energy Syst 2007;29(7):505–13. ISSN: 0142-0615.
[2] Chung KH, Kim BH, Hur D. Establishment of windows-based load management system for electricity cost savings in competitive electricity markets. Int J Electr Power Energy Syst 2007;29(10):831–40. ISSN: 0142-0615.
[3] Burdea G, Coiffet P. Virtual reality technology. 2nd ed. John Willey & Sons; 2003.
[4] Kiameh P. Power generation handbook. 1st ed. McGraw Hill Professional; 1992. p. 494.
[5] Blumel E, Schenk M, et al. Technology enhanced training at workplace: a virtual reality based training system for the technical domain. In: 1st International conference on ebusiness and e-learning proceedings; 2005. p. 57–62. ISBN: 9957-8585-0-5.

[6] Boud AC, Haniff DJ, Baber C, Steiner SJ. Virtual reality: a tool for assembly. Presence: T & VE – Mit Press Journals 2000;9(5):486–96.
[7] Wang Q, Li J. A desktop VR prototype for industrial training applications. Virtual Reality 2004;7(3–4):187–97. Springer.
[8] Li JR, Khoo LP, Tor SB. Desktop virtual reality for maintenance training: an object oriented prototype system (V-REALISM). J Comput Indus 2003;52(2):109–25.
[9] Lin F, Ye L, et al. Developing virtual environments for industrial training. Information Sciences: An International Journal 2002;140(1):153–70.
[10] Sá A, Zachmann G. Virtual reality as a tool for verification of assembly and maintenance processes. Comput Graph J 1999;23(3):389–403.
[11] Waller D, Miller J. A desktop virtual environment trainer provides superior retention of a spatial assembly skill. In: Proceedings of the conference on CHI 98 summary: human factors in computing systems; 1998. p. 339–42.
[12] Manseur R. Virtual reality in science and engineering education. In: Proceedings 35th annual conference frontiers in education; 2005. p. 8–13. doi: 10.1109/FIE.2005.1612051.
[13] Wang Qing-Hui, Li Jing-Rong. Interactive visualization of complex dynamic virtual environments for industrial assemblies. J Comput Indus 2006;57(4):366–77. ISSN: 0166-3615.
[14] Jun Yao, Jianhua Liu A, Ruxin Ning A, Zhang Ye. Assembly process modeling for virtual assembly process planning. Int J Comput Integra Manuf 2005;18(6):442–51.
[15] Angelov AN, Styczynski Z. A computer-aided 3D virtual training in power system education. In: IEEE power engineering society general meeting; 2007. p. 1–4.
[16] Guo J et al. Visualization of a hydro-electric generating unit and its applications. In: Systems, man and cybernetics, 2003 IEEE international conference, vol. 3; 2003. p. 2354–59.
[17] Pamplona Alcides, Ribeiro Manoel Filho, Sousa Marcos, Barata Pebertli, Nascimento Messias, Hounsell Marcelo. A virtual reality system for hydroelectric generating unit maintenance training and understanding. In: ISCA 19th international conference on computer applications in industry and engineering (CAINE-2006), Imperial Palace Hotel, Las Vegas, Nevada, USA; 2006.
[18] Kundur P. Power system stability and contol. Electric Power Research Institue McGrall-Hill; 1994.
[19] Klempner G, Kerszembaum I. Operation and maintenance of large turbo generators. Piscataway: IEEE Press; 2004.
[20] GLSCENE OPENGL SOLUTION FOR DELPHI. <http://www.glscene.sourceforge.net/index.php>.