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Comparison of a Digital and an experimental Physical Simulators of Load Flow and Voltage Stability Analysis

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Abstract*— In this work, a digital simulator and a physical one are presented in order to observe the behavior of load flow and voltage stability of a power system. Two five nodes networks are designed and implemented to be used as a tool in engineering studies and laboratory practices; the measurement of steady state is compared with its digital behavior simulation using Power World software. The system configuration has been extracted from one similar typical network used in the literature of power systems. Basically, it has an infinity bus, two generators, loads, six transmission lines that permit also synchronization tests and making digital and analog measurements. The generators, loads as a constant impedance (resistors, capacitors and reactors) and the infinity bus belong to a commercial brand, transmission short line models are designed using easy available materials. In addition, the use of a digital instrument meter allows information capture.

***Index Terms*—Synchronization Unit, Digital Meter, Power World, Load Flow.**

I. INTRODUCTION

For many years, engineers have been using simulation tools to predict the behavior of power systems. The challenge, as in any physical modeling and simulation tool, is to apply it effectively. Design and operation are done from the perspective of the entire system, where the loads can exhibit complex behaviors and the operating environment can have a significant influence on the system robustness. Accordingly, tools must have sufficient capability to describe the critical dynamics of complete systems, often composed of both analog and digital behaviors and spanning multiple physical domains. In load flow analysis, it is of utmost importance to calculate the voltages and currents that different parts of the power system are exposed to. This is essential to design different power system components such as generators, lines, transformers, shunt elements, and so on, because they must resist the stresses over them during the steady state operation without any risk of damages. Then, it is necessary to know the state of the voltages of all nodes in the system. With these values, all currents, and hence all active and other relevant quantities can be calculated in the system. The general objective of the present work is to describe the characteristics of a physical and a digital simulators, comparing their obtained results from the analyzed systems. The physical simulator can be useful in laboratory practices or tests in electric power courses as a tool for theory and practice knowledge, including design of elements and the use of equipment available in electric engineering. The user can get experience about simulators and power systems at the same time, without be involved in a time consuming or complex activity. This paper is organized as follows: In section I, a short introduction is given about simulators. In section II, the power network characteristics and auxiliary elements as measuring equipment are described. In section III, simulation results are presented considering a base and contingencies cases. Finally, some concluding remarks are presented in section IV.

II. NETWORK CHARACTERISTICS

In general, for educational projects is desirable to have a model with an easy relation between components and the user [1], [2]. The used five node network is small and it is seeking to minimize the time of preparing the system to be ready for test to have enough time to analyze or process data. Also, it is possible to modify its main characteristics, for example changing load and generation to other nodes and transmission lines can be moved not only in digital model but also in physical one. Both physical and digital simulators can also be used to transient stability studies, protection coordination, and short circuit and voltage stability studies. These topics belong to basic subjects in electric power systems but are not included here because this is planned to future searching.

A. Network elements

Mainly, the grid has one infinity bus, six short transmission lines, two generators or synchronous machines, five nodes (including infinity bus) and three load points. In Table I, the line constants of the short transmission lines are shown, while in Table II, values of loads, voltages and nodes are shown; the data are expressed in per unit (pu). These values are chosen because they can be obtained using common used materials [3].

Table I. Transmission line constants

Line	R(pu)	X(pu)	G(pu)	B(pu)
1-2	0.008543	0.027086	10.590921	-33.790355
1-4	0.008543	0.027086	10.590921	-33.790355
1-5	0.007234	0.021951	13.542323	-41.093108
2-3	0.007234	0.021951	13.542323	-41.093108
2-4	0.007234	0.021951	13.542323	-41.093108
3-5	0.008543	0.027086	10.590921	-33.790355

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Table II. Node type

Bus	P(pu)	Q(pu)	V(pu)	V(kV)	Angle	Bus type
1	1.92	1.44	1.0218	212.54	-0.343	Generation
2	1.44	1.44	1.0103	210.15	-0.862	Load
3	.....	.....	1.05	218.4	0	slack
4	1.44	1.44	0.9961	207.19	-1.189	Load
5	1.44	1.44	1.0154	211.21	-0.73	Load

The equipment to develop this work has the following characteristics: an infinite bus represented for a phase of a 60 Hz ac (alternating current) voltage source with 208/120 Vrms (Figure 1), two synchronous 120 VA three phase generators (Lab-Volt) of 60 Hz 120/208 Vrms with 1800 RPM (Figure 2), resistance and inductive reactance modules (Lab-Volt) of 300, 600 and 1200 ohms that simulates the load. Also in Figure 3, a Lab-Volt dc machine is included with a 120 V variable source, which is used as a prime motor (mechanic source) of synchronous generators; and a couple of three phase synchronization modules (Lab-Volt) that makes possible to connect the generators to the system with a synchronization procedure, as it is shown in Figure 4. Short transmission line models involves 20 AWG and 22 AWG size cable, their construction consist on placing the isolated cable inside a piece of soft iron used as a magnetic circuit to increase the inductance. Both size of cables are used to build windings, the length of the conductor is 100 meters, but the conductor is already a winding. Only it is necessary to unpackage the cable and get it into the iron piece, which is also cheap. The construction is made with commercial cable with 20 (one pole) and 22 (two poles) AWG sizes. A photo of the six transmission lines is presented in Figure 5.

Fig. 1. Lab-Volt ac and dc voltage sources

Fig. 2. 120 VA three phase synchronous machine (Lab-Volt)

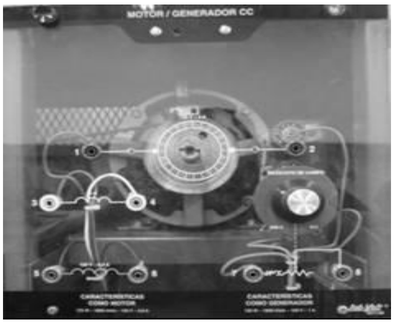

Fig. 3. Lab-Volt dc Motor

Fig. 4. Lab-Volt Synchronization module

Fig. 5. Transmission line models

Because the transmission line model has a resistance connected in series with an inductive reactance, these values must be known. The resistance can be calculated if a dc voltage is applied to the winding terminals already in the iron, then the voltage is divided over the current and the dc resistance is obtained. A simplification is giving assuming a negligible skin effect, thus the resistance in dc is equal to ac resistance (R). Then an ac voltage is applied across winding to get the ac impedance magnitude (Z). To obtain the reactance X, equations (1) and (2) are used,

$$Z = \sqrt{X^2 + R^2} \quad , \qquad (1)$$

$$X = \sqrt{Z^2 - R^2} \quad . \qquad (2)$$

Tables III and IV show the calculated physical values of the transmission lines. Figure 6 shows the set of lines.

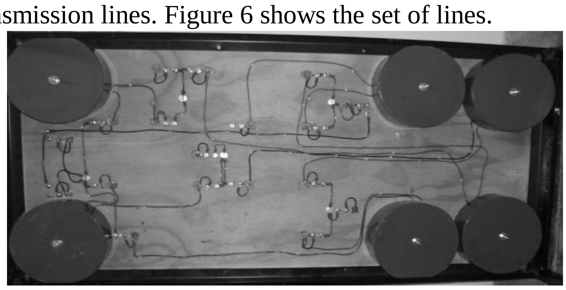

Fig. 6. Set of transmission line models to physical tests, developed at UAEM

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Table III. Impedance of transmission line model 1 (20 AWG conductor, one pole).

Rcd(ohms)	Zca(ohms)	X(ohms)	ang(degree)	f(Hz)	L(mH)
3.08	10.24	9.77	72.50	60.00	25.90

Table IV. Impedance of transmission line model 2 (size 22 AWG conductor, two poles).

Rcd(ohms)	Zca(ohms)	X(ohms)	ang(degree)	f(Hz)	L(mH)
2.61	8.33	7.91	71.76	60.00	20.99

Analog ammeters and voltmeters are used only to measure magnitudes of currents and voltages, in order to monitor the load in the equipment or making several adjusting to a specific state operation. Also a tachometer is useful to measure RPM of the generator during the synchronization process. The digital instrument AEMC Power Pad model 3945-B meter and data acquisition [4] shown in Figure 7 is also used to set specific quantities of real and reactive power of synchronous machine, to measure voltage phasors (especially the angles) and power flow in lines or to synchronize units. During the tests, voltage and current are measured using analog voltmeters and analog ammeters of Lab-Volt, with capabilities of 250 V and 25 A, which can be also used to get the signal current from physical model TC clamp-on. For this research, the effect of proximity only takes importance when the iron cores of transmission lines are stacked, but if they are in the same plane, the impedance not present changes. Figure 9 shows the minimum distance of iron core where coupling effect can be neglected, this is of 6 centimeters. To support last sentence, it was necessary to make several physical measurements using two windings of the transmission line model. The impedances of the windings were measured taking into account the separation of each other, obtaining that the impedance has not dependence of separation if the plane is horizontal, but the impedance changes if the windings are stacked. This effect can be observed in Figure 8 and 9. In all remaining equipment the influenced by proximity can be ignore. It is important to note that transmission lines models were developed at UAEM.

Fig. 7. Meter and data acquisition digital instruments AEMC Power Pad model 3945-B

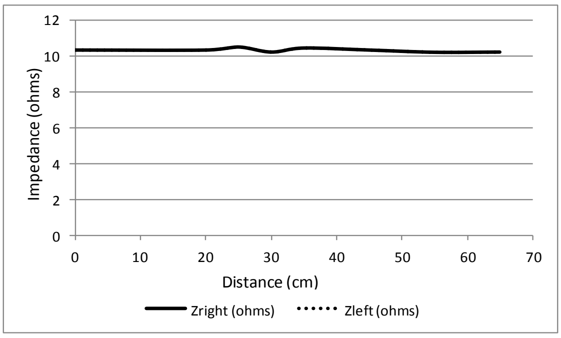

Fig. 8. Behavior of line impedance versus horizontal distance separation

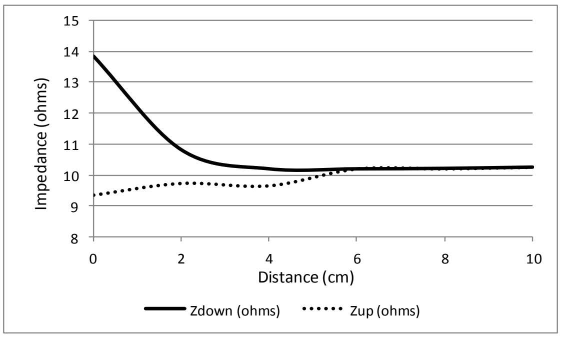

Fig. 9. Behavior of line impedance versus vertical distance separation.

B. Base quantities

Base quantities are chosen to take a direct relation between a simulation model and a real power system. Base voltage is 208 V and base power is 120 VA correspond with the nominal values of three phase generators used in laboratory. These base values allow to match with the impedance of a power grid of 208 kV with a base power of 120 MVA. Later, this consideration will be used in digital simulation, where a direct relation between powers and voltages exists. The base currents of physical and real system can be calculated from equations (3) and (4) as follows,

$$I_{base(208\text{V},120\text{VA})} = \frac{120\text{ VA}}{(\sqrt{3})(208\text{ V})} = 0.333\text{ A}, \quad (3)$$

$$I_{base(208\text{kV},120\text{MVA})} = \frac{120\text{ MVA}}{(\sqrt{3})(208\text{ kV})} = 333\text{ A} \quad (4)$$

Current of digital simulation will have a value of one thousand times current physical test. Also, 120 MVA in digital process is related with 120 VA in physical process.
Hence, base impedance is:

$$Z_{base} = \frac{(208\text{ V})^2}{120\text{ VA}} = \frac{(208\text{ kV})^2}{120\text{ MVA}} = 360.533\,\Omega \quad (5)$$

Impedance, resistance, and reactance of transmission line model 1 are shown in Table V. These values are similar to transmission line model 2, shown in Table VI.

C. Network interconnection

The main advantage of the network interconnection is its small size and the simplicity of the system. As a result, data

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are easily obtained; the analysis process is also simple. The chosen grid is similar to published one in the classical literature of power systems [1] to solve load flow problems. The network has the possibility of controlling voltage with nodes 1 and 3, which can be considered as generation nodes. Points 2, 4 and 5 are load nodes. The one line diagram of the five nodes system is shown in Figure 10. The base case has the following characteristics: in node 1, each machine is delivering 96 MW and 72 MVAr, it means that the machine is working with a power factor of 0.8 lagging and 120 MVA. The load in buses number 2, 4 y 5 are 144 MW and 144 MVAr (each node) which is 203.6 MVA with a power factor (*PF*) of 0.707 lagging. This case is selected because a lag low power factor stresses the grid, making possible the load flow near to voltage collapse. In digital model, the three phase power is used while in physical one single phase power is used.

Table V. Base quantities and impedance of transmission line model 1 (size 20 AWG, one pole)

Vbase (V)	Sbase (VA)	Zbase (ohms)	Rcd(pu)	Zca(pu)	X(pu)
120.00	40.00	360.00	0.008543	0.028401	0.027086
208.00	120.00	360.53			

Table VI. Base quantities and impedance of transmission line model 2 (size 22 AWG, two poles)

Vbase (V)	Sbase (VA)	Zbase (ohms)	Rcd(pu)	Zca(pu)	X(pu)
120.00	40.00	360.00	0.007234	0.023112	0.021951
208.00	120.00	360.53			

To get a load of 144 MW (3x48 MW) and 144 MVAr (3x48 MVAr) having reactance and resistance elements, equations (6), (7) and (8) are used:

$$R = \frac{(208\,\text{kV})^2}{144\,\text{MW}} = \frac{(120\,\text{V})^2}{48\,\text{W}} = 300\,\Omega \,, \qquad (6)$$

$$X = \frac{(208\,\text{kV})^2}{144\,\text{MVAr}} = \frac{(120\,\text{V})^2}{48\,\text{VAr}} = 300\,\Omega \,, \qquad (7)$$

$$PF = \frac{144\,\text{MW}}{203.6\,\text{MVA}} = 0.707 \qquad (8)$$

Resistance and reactance of 300 ohms can be obtained directly from the modules; three resistances and three inductances are required because the loads are connected in nodes 2, 4 and 5. In the development kit, it is necessary a load on each node of 48 W and 48 VAr. In the digital model, three phase system is considered but the physical one has only one phase. It means that the power relation between digital to physical models is 144,000,000 to 48, in voltages 208,000 to 120 and in currents 1,000 to 1. Thus, the slack in node 3 is delivering to the network 248 MW and 309 MVAr in digital case or 82.67 W and 103 VAr in physical one. In Figure 10, the equivalent impedance of the six transmission lines are shown. As it can be observed only two different lines are included in the grid: one value for 1-2, 1-4, 3-5 and other one for 1-5, 2-3, 2-4. Nodes connection allows also contingencies into the grid, making the use of simulator an excellent tool for training in operation and analysis systems. Figures 10 and 11 can be compared. The first one corresponds to digital simulator and second one to physical simulator.

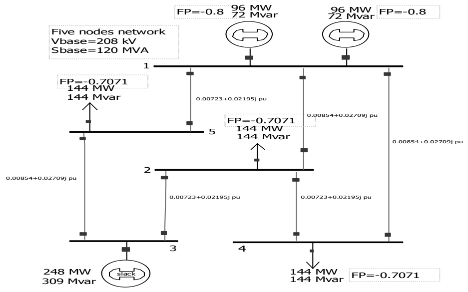

Fig. 10. One line diagram of five nodes network showing the three phase values for digital calculation

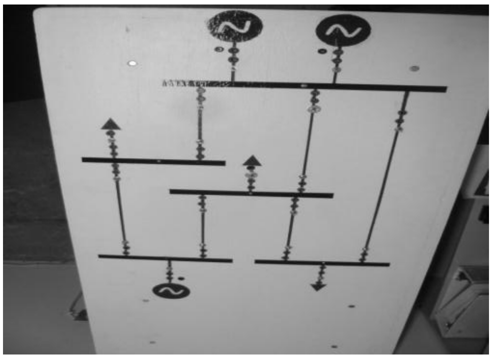

Fig. 11. Physical simulator to load flow studies, developed at UAEM

III. SIMULATION

Physical measurement are compared with the values obtained from digital simulation of Power World, base and contingency cases are here included. To carry out the physical simulation is necessary the complete network interconnection, it means that lines and loads are connected, generators delivering a specific power, infinity bus with the desired voltage and all the measurement equipment is ready, a photo of this required array is shown in Figure 12.

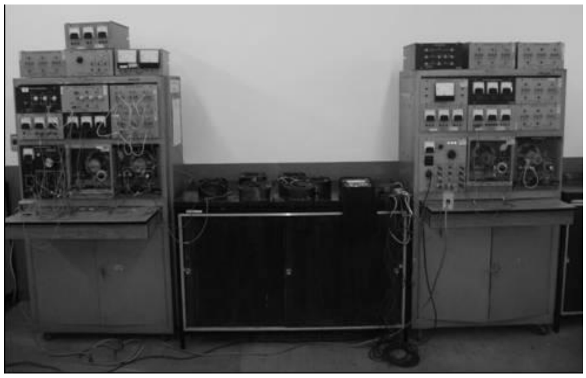

Fig. 12. Complete physical simulator to load flow and voltage stability

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Table VII. Measurement of real and reactive power and current from the development kit to base case.

Line	W	VAr	A
1-2	18	12	0.2
1-4	32	29	0.35
1-5	15	7	0.13
2-3	48	56	0.6
2-4	17	20	0.23
3-5	32	41	0.45

D. Load flow base case

It is possible to take into account the given solution of the base case using Power World to obtain the initial conditions. The main objective in this case is to obtain the voltage and power in order to have a general image of the network. In Figure 13, the load flow in transmission lines and voltages on buses from Power World are shown. The measurement of these quantities from physical simulator are shown in Tables VII and VIII.

E. Load flow contingency case

The objective of making test considering elements off has a big importance inside power systems. Planning, maintenance and operation in many countries take into account at least the loss of a single element [6]. Since an educational point of view, this fact allows to get new knowledge of the system and gives a general physical idea of the behavior of an electric grid in a possibly emergency state [1], [6]. This information helps to develop the skill of taking alternatives and being prepared in emergency or contingency situations. In this case, the element considered to be off is the line from bus 2 to bus 3. This element has been chosen because it provides the lowest voltage (worst case) for the same operation condition and shows a critical behavior of the grid. Figure 14 shows the load flow and voltages with a contingency of line 2-3, also this result can be compared with physical values of Tables IX and X. In this operation state, the physical and digital values are similar despite of different load model. Only with contingency, the system goes to the nose of P-V curve. Note that the grid is stressed because the low magnitude of voltages and the relative large angles values are presented.

A sample of the measurement is shown in Figure 15 where a comparison of voltages in node 3 and node 4 is made also in Tables IX and X we can see its corresponding load flow and phasor voltage values.

Table VIII. Measurement of node voltages of five nodes to base case.

Node voltages (V)				
V1	V2	V3	V4	V5
$123\ V \angle -0.3^0$	$122\ V \angle -0.9^0$	$127\ V \angle 0^0$	$120\ V \angle -1.3^0$	$122\ V \angle -0.8^0$

Table IX. Measurement of real and reactive power and current from physical simulator to contigency case.

Line	W	VAr	A
1-2	43	43	0.60
1-4	43	43	0.60
1-5	30	49	0.51
2-3	0	0	0.00
2-4	0	0	0.00
3-5	71	92	1.06

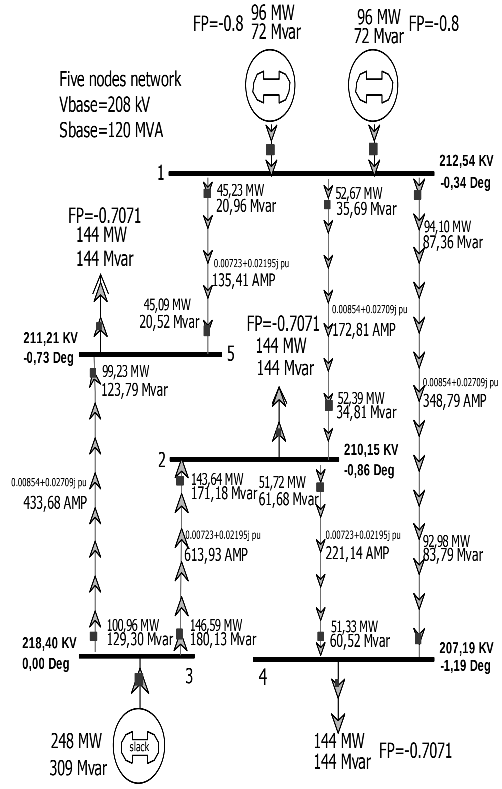

Fig. 13. One line diagram of five nodes network for base case (Power World solution).

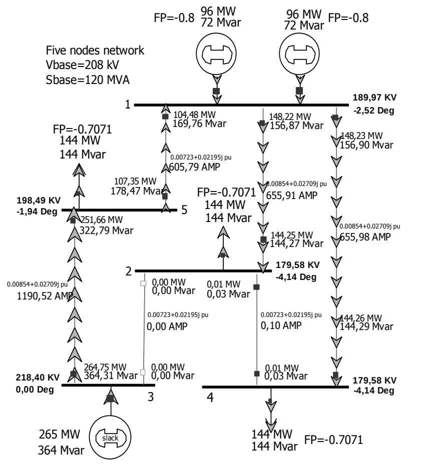

Fig. 14. One line diagram of five nodes network for contingency case (Power World solution).

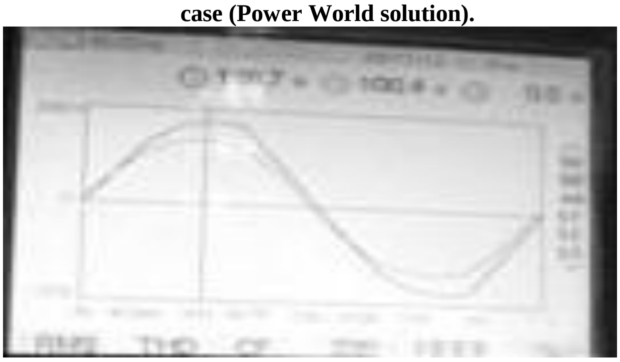

Fig. 15. Voltages of nodes 3 and 4 during the contingency shown in Figure 14. Voltage values are shown in Table X.

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F. Voltage collapse

To carry out the test of voltage collapse in the digital grid implies to increase the load, but this must be compared with the behavior of physical grid. To set the digital system where voltage collapses a total power of 1506 MW (or 502 W in physical network) is required. Figure 14 is related with base case and P-V curves shown in Figures 16 and 18 where the nodal phasor voltage is function of load power.

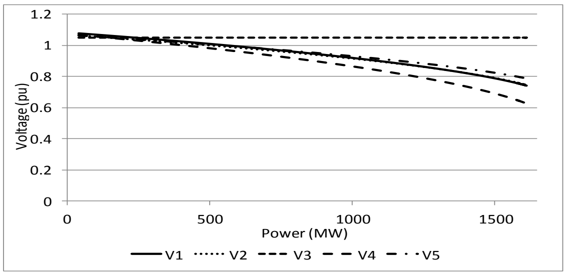

Fig. 16. P-V curves of the five nodes grid for base case.

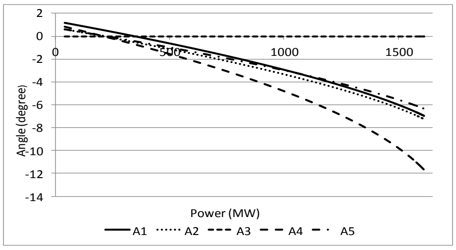

Fig. 17. Angle-Power curves of the five nodes network for base case

When a contingency occurs in line 2-3, the system almost gets the collapse point (Figure 18). The nodal load increases the demand of power, as it can be seen in the voltage values from digital simulation. P-V curve is shown in Figures 18 and 19, where the collapse point is 588 MW, it means that in each load bus (2, 4 and 5) there is a demand of 196 MW (65.3 W for physical grid) or a total demand of 588 MW (196 W for physical grid). This is the unique case that can be simulated in the physical simulator due to the currents and load flow power without risk or overload in the elements. The physical measures of values of nodes voltage phasors are shown in Table XI. In Figures 16 and 18, it can be observed that the node number four is the "weakest" talking about voltage support [6]-[8], the collapse values is near from 0.6 pu. On the other hand, the phasor angles of the voltages show the system can reach values up to -10 and -12 degrees from the depicted cases in Figures 17 and 19, respectively. To define the collapse point in a real network, it is unnecessary to reach so low voltages as 0.6 pu or 0.65 pu. Frequently, the minimum permissible value is very close to 90% of the nominal voltage, normally the weak nodes correspond to load ones.

Table X. Measurement of node voltages of five nodes physical model to contigency case. Related with Figure 18.

Node voltages (V)				
V1	V2	V3	V4	V5
108 V ∠ -2.8°	104 V ∠ -4.0°	126 V ∠ 0°	100 V ∠ -3.8°	114 V ∠ -2.1°

Table XI. Measurement of node voltages of five nodes physical model to contigency case (tip of the nose). Related with Figure 19.

Node voltages (V)				
V1	V2	V3	V4	V5
101 V ∠ -5.0°	90 V ∠ -8.0°	126 V ∠ 0°	90 V ∠ -8.0°	112 V ∠ -3.0°

In Figures 16 and 17, the behavior of voltage versus real power and voltage angle versus real power can be observe. This fact is related with voltage collapse study, relatively simple using digital simulator but it is necessary to pay attention in load because in digital model, the load is considered as a constant power but in the physical one the load is expressed with a constant impedance.

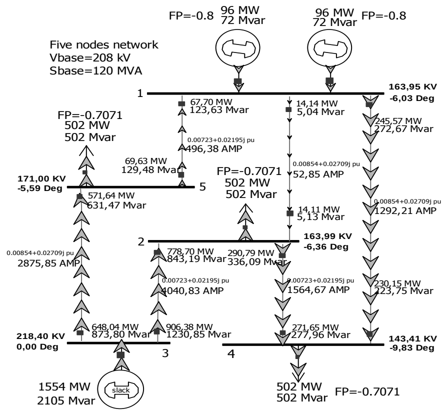

Fig. 18. One line diagram of five nodes network for tip of the nose case (Power World solution).

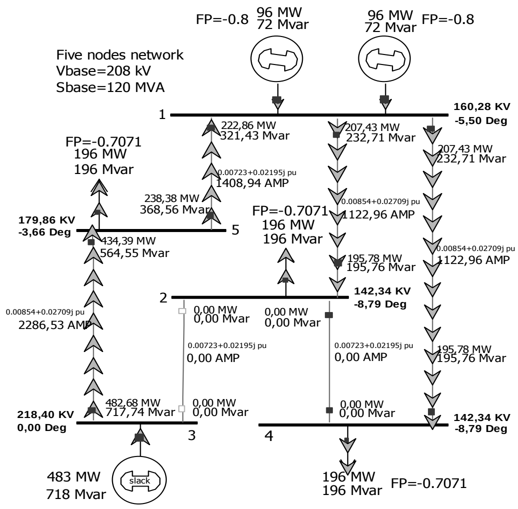

Fig. 19. One line diagram of five nodes network for tip of the nose contingency case (Power World solution).

IV. CONCLUSION

Data from physical and digital simulators match. In general, voltages and load flows have similar values despite of modeling load. When the grid is close to voltage collapse point the behavior of digital and physical models is a little different of that obtained from base case. Mainly, it happens because in digital case, load model is a constant power and constant impedance is used in physical one. Both simulators are useful to understand how the basic quantities of voltage and current (load flows) can be controlled. Practicing with

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measurement equipment gives the skill of understanding technical concepts and operation of a power electric system. The user gets knowledge about electric power systems and interacts with measurement equipment, often used in grid tests. The use of these simulators allows making the knowledge reinforce of students and the training of teachers having, considering low cost for these activities. Implementation of these two simulators allows changing of load nodes and generation points interchange transmission lines. The change of the initial condition is easy due to the relatively small size and simplicity of the grid. The user gets involve in design of equipment because it is possible to measure and calculate short line constants of physical models. Due to the design of transmission lines the proximity effect must be considered only if the lines are stacked.

V. ACKNOWLEDGMENT

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REFERENCES

[1] W. D. Stevenson J.R., "Análisis de Sistemas Eléctricos de Potencia", McGraw Hill, 1992.

[2] A. R. Bergen and V. Vittal, "Power Systems Analysis", Prentice Hall Inc., second edition, 2000.

[3] L. Cisneros Villalobos and M. Tecpoyotl-Torres, "Gradient Method Applied to Load Flow Equations to Power System Voltage Stability Evaluation", Mexican Journal of Scientific Research, Vol. 1, No. 1, pp. 24-41, Jul-Dec 2012

[4] User Manual of AEMC Power Pad model 3945-B, 2010.

[5] Power World Corporation Web Site: http://www.powerworld.com, accessed Jun 15th, 2012.

[6] Guide to WECC/NERC Planning Standards I.D: Voltage Support and Reactive Power, Western Electricity Coordinating Council, March 30, 2006.

[7] Clark, H. K, "New Challenges: Voltage Stability", IEEE Power Engineering Review, April, pp 33, 1990.

[8] Carson W. Taylor, "Power System Stability and Control", McGraw Hill, 1994

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L. Cisneros-Villalobos was graduated as Electrical Engineer from Autonomous University of Morelos State (UAEM), in 1996. He received the Master degree in Engineering from National Autonomous University of Mexico (UNAM), in 2002. He is a Ph. D. student in the Research Center of Engineering and Applied Sciences (CIICAp) at the UAEM. His main research interest and experience includes Operation of Electric Power and Distribution Systems in steady and dynamic states, Power Quality, Electrical Transients and Alternative Sources of Energy. He has been titular teacher in UAEM since 1998 where he is currently research professor.

M. Tecpoyotl-Torres received the Mathematician degree from the Autonomous University of Puebla (UAP), Mexico, in 1991. In this University, she was graduated as Electronic Engineer in 1993. She received the M.Sc. and Ph.D. degrees in Electronics from National Institute of Astrophysics, Optics and Electronics (INAOE), México, in 1997 and 1999, respectively. Dr. Tecpoyotl works, since 1999, at CIICAp of UAEM, Mexico, where she is currently titular professor. Her main research interest includes MEMS and Microwave devices. She holds the status of National Researcher (SNI, level 1).

J. G. Vera-Dimas was graduated from the Technologic of Morelia as Electronic Engineer. Member IEEE since January 2005. He received the award "EGRETEC 2009" by the Association of Graduates from the Technological Institute of Morelia. He received the M.Sc. degree in Electronics from the UAEM. Nowadays, he is a Ph. D. degree student in the CIICAp at UAEM. He has currently two patents in revision.