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Security Margin Increase by Voltage Stability-Oriented Emergency Power Injection

G. C. Barreto-Mederico, E. Caraballo-Henríquez, and C. A. Goyo-Barrientos, *Member IEEE*

***Abstract*— A methodology to locate and size conveniently new power generation in order to rescue the voltage profile in a power system near to voltage collapse is presented in this paper. The analysis is based on the maximization of the voltage of the whole power system at any point within the secure operations limits by using a special Optimal Power Flow that takes into account the orientation provided by the sensitivities generated during the process of optimization. Under this approach, emergency measurements were designed to be implemented in the South-West Power System of the National Grid of Venezuela as part of a short-range plan. The solution showed how the voltage profile in that system is increased by the injection of new power generation that could be provided by emergency plants deployed in few but key points of the network**

***Index Terms*—Voltage Stability, Voltage Collapse, OPF, Emergency actions, Security, Distributed Generation**

I. Nomenclature

VNG	Venezuelan National Grid
SWPS	South-West Power System
DG	Distributed Generation
OIPF	AC optimal integral power flow

II. Introduction

Venezuela's Power System has been developed to take advantage of the great hydroelectric resources in the south-east region for long time. Not in vain, hydroelectricity supplies about 70% of the demand for electric power. Being the main load centres very far from the generating stations in the south-east, long transmission systems at 765 kV, 400 kV, 230 kV, and 115 kV, were developed to transmit those large blocks of power and then to distribute them to the consumers on the other side of the country.

However, the expansion of this HV network has been behind schedule for several reasons resulting in a power system temporarily insufficient for the always-growing demand.

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G. C. Barreto-Mederico is with FUNDELEC, Torre PDVSA-Sur, Piso 6, Av Libertador, Caracas 1050 (e-mail: barnunster@gmail.com).

E. Caraballo-Henríquez is also with FUNDELEC, Torre PDVSA-Sur, Piso 6, Av Libertador, Caracas 1050 (e-mail: elenach66@gmail.com).

C .A. Goyo-Barrientos is also with FUNDELEC, Torre PDVSA-Sur, Piso 8, Av Libertador, Caracas 1050 (e-mail: kgb@ieee.org).

In the past, only rotor angle stability problems worried the Venezuelan planners and operators, especially about the transmission of power through some long corridors with little generating reserve capacity on the receiving end. But, the effects of these vulnerabilities were confined regularly to the local networks reducing the impact over the whole power system.

Recently, the backbone of the Bulk Power System has been in trouble. Heavily loaded in a daily basis with many hours exceeding the security limits, the Venezuela's National Grid (VNG) is subject to the occurrence of partial and total blackouts. The transition from the *Alert* condition to the *Emergency* condition [1] is relatively more frequent as load demand continues growing and the new infrastructure has not put in service yet.

In the meantime, emergency actions have to be implemented as palliatives but its design is complex since multiple problems of different nature but interdependent each other are now present especially one related to Voltage Stability in the South-West Power System (SWPS). The worst thing is this could drive the whole VNG to the collapse

III. Venezuelan National Grid

The Venezuelan Bulk Power System is shown in Figure 1 where the biggest Hydroelectric Central Station over the *Caroní* river basin in the south-east, stands out in a circle while the main load centres, Caracas, the capital, in the mid-north and, Maracaibo, the second biggest city in the western, are also enclosed in a circle respectively. Additionally, the South-West region is marked in a dotted line where a systemic long-range voltage stability problem has been risen up for a couple of years ago.

IV. Voltage Stability problem in the Venezuelan National Grid

The South-West Power System of the VNG supplies the demand for electric power of The Andes, a mountainous region. A single-line of this system is shown in Figure 2. There is a long distance between this load centre and the main hydroelectric generating complex in the south-east, therefore the angle deviation between local and VNG generators is maximal. This condition has always been considered as a security weakness and thus, it has required its supervision. Notwithstanding, the most common expected thread considered has been a rotor angle stability event.

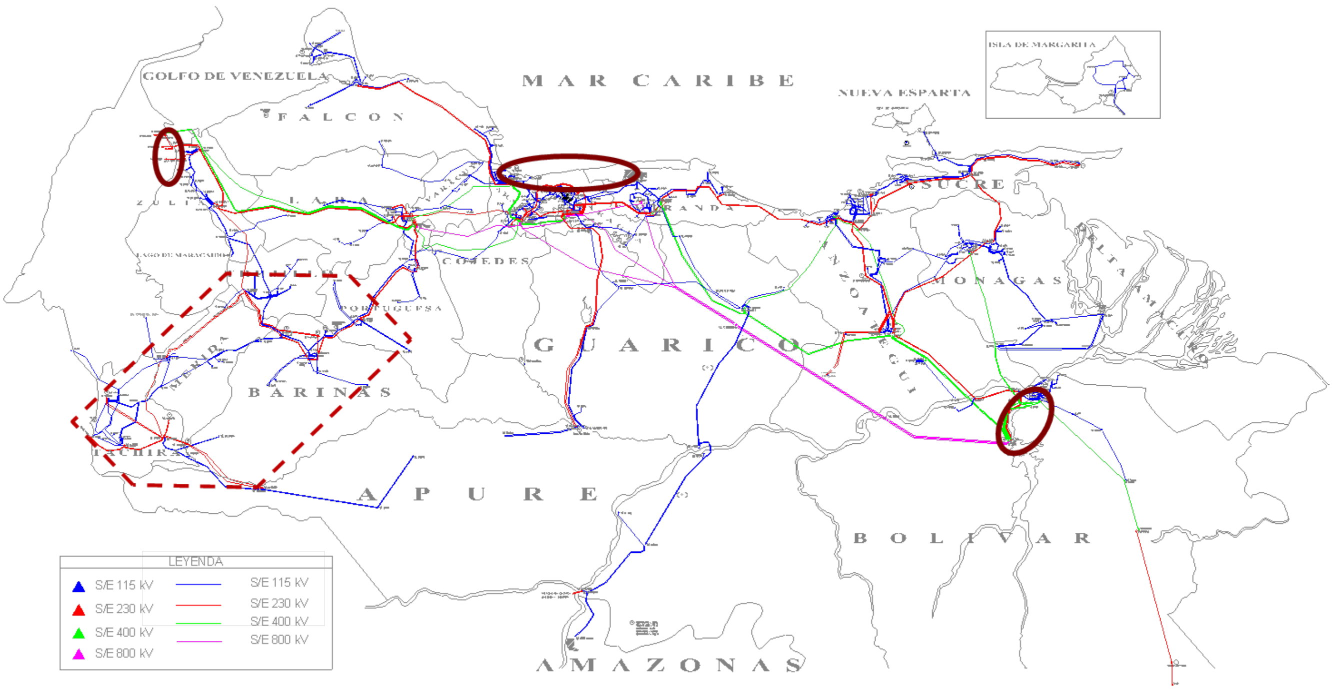

Fig. 1. Geographic single-line diagram of the Venezuela’s Interconnected Power System

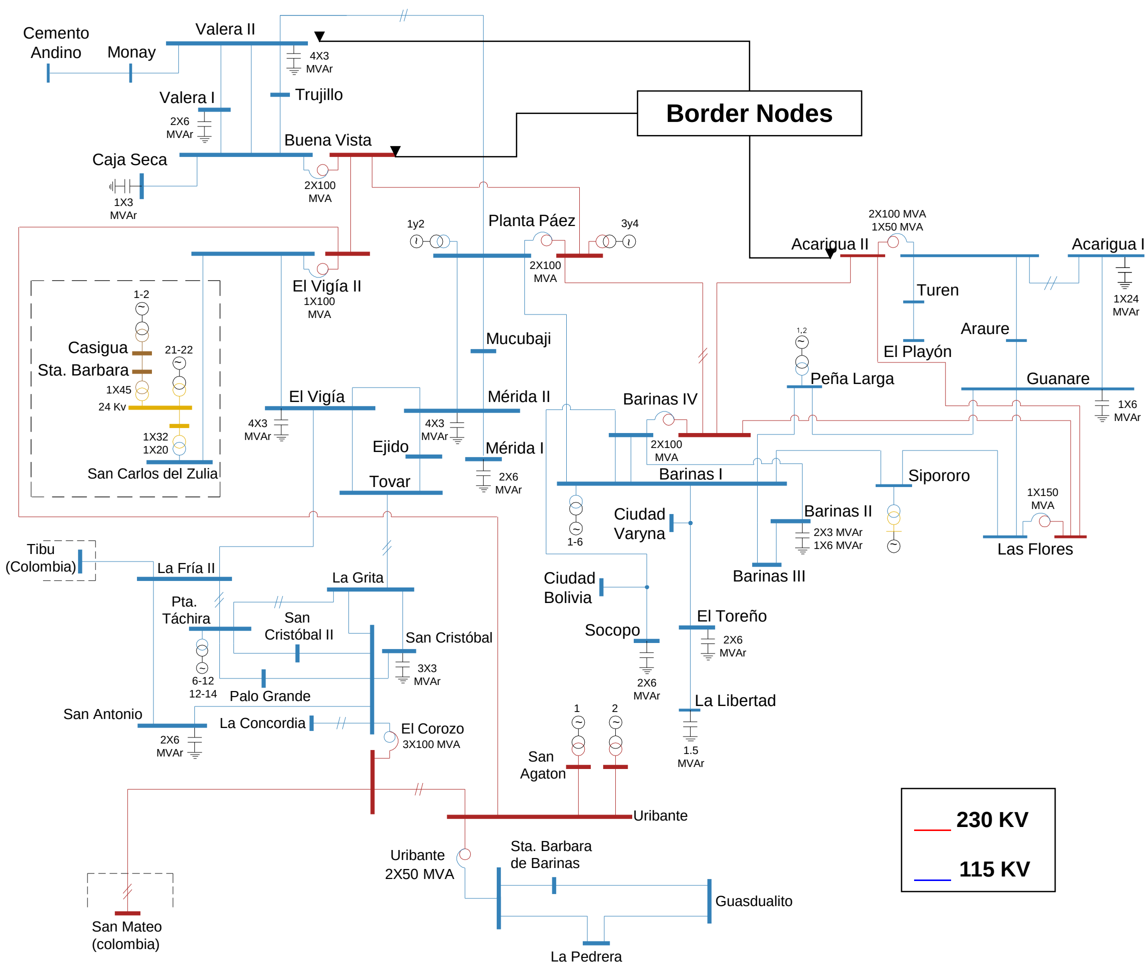

Fig. 2 Single-line diagram of the sub-system under study: Venezuela’s South-West region.

In recent years, evidence of the presence of a long-term voltage stability phenomenon has appeared in the SWPS. A very low voltage profile in all nodes of the system at 230 kV and 115 kV of slow progress has been the reason for preventive load curtailment especially at peak hours. The effects over the VNG have been spreading out very fast increasing a risk of a general blackout even making 765 kV - EVH Transmission System suffer from low voltage profile at main nodes

V. Problem

The reinforcement of the existing infrastructure is required in short-time since the local generation deficit is regarded as one of the main reasons for the appearance of a voltage stability problem in the SWPS. The permanent solution is not expected to be developed as fast as needed so emergency plants look convenient to be installed to increase the operation security margin for the whole VNG. Fortunately, there are 141 MW available of small reciprocating piston engine distributed generators which are part of the equipment of a Distributed Generation (DG) programme for quality improvement of the electrical service in some critical zones of Venezuela. Although this option is neither efficient nor permanent, the immediate availability of the generators, rapid installation, and solved fuel logistics make it enough attractive, yet, the optimal location and size of this equipment must be defined so that this additional power injection can impact effectively on the SWPS voltage profile.

The available diesel engine-generator set comes in two ratings, one of 1.8 MVA and other of 1 MVA each to be grouped in generating stations for a total of 15 MW and 8 or 4 MW respectively. Those capacities are characteristic of DG Technology but the interconnection with the VNG would be at 115 kV for this special case

VI. Approach

The problem will be solved by using an AC Optimal Integral Power Flow (OIPF) the objective function of which is the SWPS voltage profile maximization at all the nodes inclusive.

This method with another objective function is the basis of a prototype tool called ***THOR*** that uses an integral OPF for solving the generation and transmission expansion at the same time, considering both investments and operations costs [2].

During the process of the OIPF convergence, active and reactive power sensitivities at candidate nodes for new generation are analysed respectively. The planner can determine by inspection of these signals, the most effective nodes on the system voltage for power injection. The rest of the decision-making process is complemented after meeting the resulting new generation with the available DG units and checking for links overloading. Variables as fuel transport and storing logistics and interconnection transformers for the new DG arrays are also considered.

VII. Model

The AC optimal integral power flow (OIPF) described in [2] is a special variation of an OPF where the objective function includes both investment and operation costs. On this comprehensive optimization, the equations have been adapted to the real problem in AC so that the physical laws are satisfied fully. Furthermore, reliability, quality, environment, and cost criteria complying with the regulation and other policies can be considered in the final design.

However, for this analysis, the original cost objective function has been replaced by the sum of all the voltages at all the power system nodes, as follows:

$$Max \sum_{i}^{ni} V_{p\,i} \tag{1}$$

Subject to:

$$P_{g\,\min} \leq P_{pg} \leq P_{g\,\max} \tag{2}$$

$$Q_{g\,\min} \leq Q_{pg} \leq Q_{g\,\max} \tag{3}$$

$$\mathrm{V}_{\min} \leq \mathrm{V}_{\mathrm{pi}} \leq \mathrm{V}_{\max} \tag{4}$$

$$\delta_{\min} \leq \delta_{\mathrm{pi}} \leq \delta_{\max} \tag{5}$$

$$\mathrm{P_{pg}} + \sum \mathrm{Pvin_{pi}} - \mathrm{D.Act_{pi}} = 0 \tag{6}$$

$$Q_{pg} + \sum Qvin_{pi} - D.\mathrm{Re}\,ac_{pi} = 0 \tag{7}$$

And computing the total cost for the SWPS as a plus:

$$TotalCost = \sum_{p}^{np} \tau_p \sum_{g}^{ng} CO_g P_{pg} + \sum_{g}^{ng} \frac{k_g}{N} Pm_g + \sum_{l}^{nl} \frac{k_l}{N} L_l Tm_l \tag{8}$$

Where:

τ_p	Demand block durations
p, g, l, i	Demand blocks, generators, transmission lines, and nodes index, respectively
np, ng, nl, ni	Total number of demand blocks, generators, transmission lines, and nodes, respectively
CO	Unitary operation costs including O&M
P_{pg}	Generator power delivery in each block of demand
N	Numbers of periods in the year according to the demand time scale (e.g.: yearly: N =1; monthly: N =12; daily: N =365; hourly: N =8760)
k_g	Annualized marginal cost for the installation of one KW at one node (US$/kW-year)
Pm_g	Maximum power required of each generator, among all generator power of each demand block
Tm_l	Maximum capacity required of each line, among all line power capacities resulting at each demand block
L_l	Length of each line
k_l	Annualized marginal cost for the construction of one Kilometre of transmission line (US$/MW-Km-year)
P_{min}, P_{max}	Minimum and maximum limits for the active power that can be delivered to the system by each control-active element (e.g. A generator)

Q_{min}, Q_{max}	Minimum and maximum limits for the reactive power that can be delivered to the system by each control-active element (e.g. A generator, a SVS, an area interchange bus)
V_{pi}	Magnitude of the voltage resulting at each demand block (p.u.)
V_{min}, V_{max}	Minimum and maximum limits for the voltage magnitude at each node (p.u.)
δ_{pi}	Phase Angle of the voltage at each node resulting at each demand block (radians)
δ_{min}, δ_{max}	Minimum and maximum limits of the phase angle of the voltage at each node (radians)
$Pvinc_{pi}$, $Qvinc_{pi}$:	Active and reactive power flows resulting at each demand block, of all the links associated with each node, respectively (MW/MVAr)
$D.Act_{pi}$, $D.Reac_{pi}$	Active and reactive power for the load demand at each node for each demand block, respectively (MW/MVAr)
TotalCost	Total Power System Investment and Operation Costs per unit of time considered (e.g. US$/h)

The used equations are the corresponding ones to a power flow in alternating current to solve a nonlinear and non-convex problem.

Although, the formulation of the optimization problem allows processing even 8,760 hours of a yearly load curve with no other restrictions than computing time, only the maximum demand block (p=1) coming from a statistical daily load curve analysis was used for this study with a duration of four hours (τp=4), since cost minimisation was not the target and load curtailment occurred at load peak hours

Having typified the SWPS problem as one of Voltage Stability, the measures designed through the maximisation of the whole voltage profile is expected to increase the security of the region.

Besides, this optimisation is also constrained by the voltage phase angle which could help evaluating the robustness of the resulting transmission links and generation injections, and subsequently, the power system stability at a basic level.

VIII. Study Network

The Andes region represents 10% of the territory of Venezuela and occupies 80,000 Km^2 with 3 states: *Trujillo*, *Mérida* and *Táchira*. Its transmission network is interconnected to the VNG, however, simulations will be done not only with the local network nodes but with those of neighbouring states: *Apure, Barinas, and Portuguesa*, strongly related with the Andes'. Thus, 56 nodes have been simulated from this enlarged system but 5 nodes of the states *Cojedes* and *Carabobo*'s network have been added since they are part of the border of the power system simulated for this analysis. In total, the number of nodes of the simulated network is 61 and can be seen in Figure 2 in detail.

IX. Diagnosis

The previous situation of the SWPS is shown in the Figure 3, where the conditions of the system for the day of maximum power demand in May 2008 are represented.

Columns depict the active and reactive power at the generating nodes according to the generation dispatch of that day.

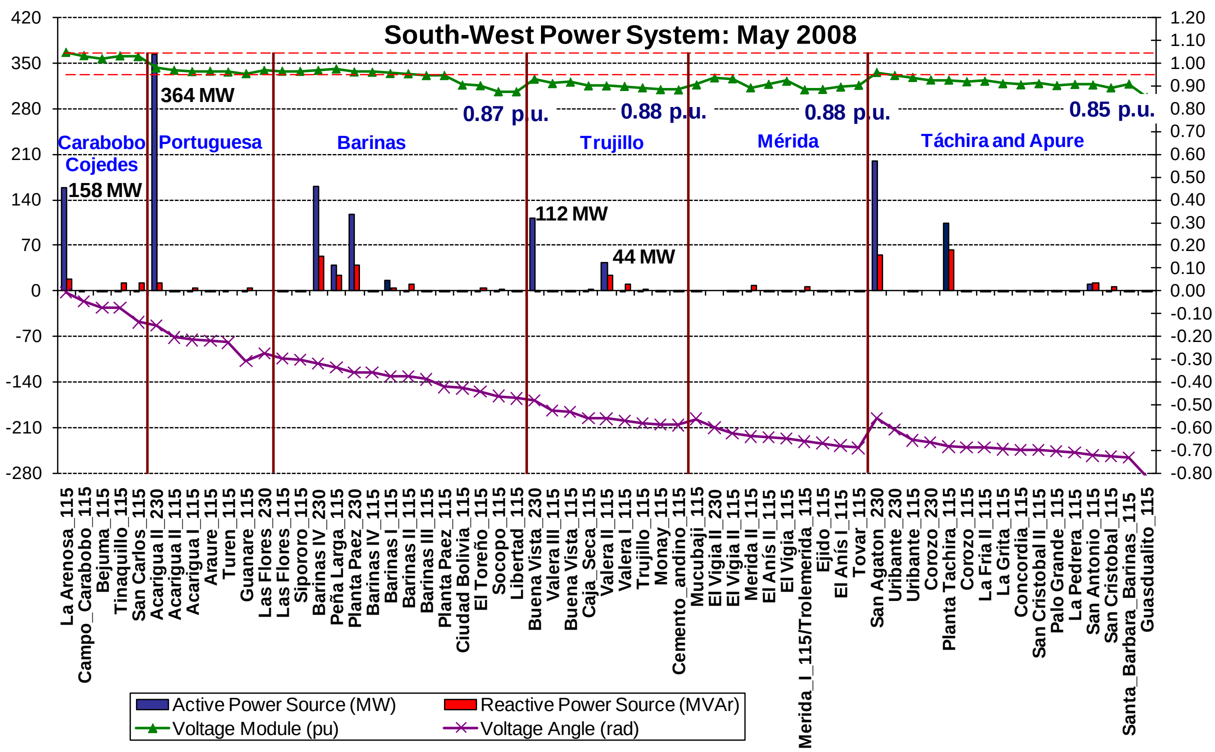

Fig. 3: Power injections, voltage profile and phase angle deviation at the nodes of Venezuela's South-West Power System.

The upper variable line represents the per unit nodal voltage. This resulting voltage profile should be remained in the range between the upper and lower constant lines in order to meet the ±5% VNG Voltage Criteria. Voltages below 0.92 per unit in the transmission system are highly risky.

The lower line represents the angle deviation in radians of the nodal voltages with respect to the border node called *La Arenosa*. The angle of *La Are*nosa voltage is supposed to be as well separated by 0.5 radians from VNG reference angle which is associated with the big Hydroelectric Central Station in the south-east.

In the diagram of Figure 3, nodes have been ordered in the way power flows, that is to say, from the bulk power system (*La Arenosa*) to the physically and electrically farthest one (*Guasdualito*) or also, from *Cojede*s state to *Táchira* state. That was possible because the transmission power system has a likely-radial design and local generation is not sufficient as reversing the power direction. To supply a demand of about 1,200 MW, the SWPS counts on a maximum generating capacity of 650 MW only. The rest has to be imported from the VNG being *Acarigua 230 kV* the main point for this.

A very low voltage profile is observed in the whole power system as expected for a condition preceding a voltage collapse event. In fact, the voltage profile is out of the voltage criteria range at any node and it can be as low as 0.85 per unit at *Guasdualito*. The quality of the electrical service in these zones has confirmed these simulations.

Additionally, the nodal voltage angle deviation falls down as far as the node is from the main source. The difference can be as big as 0.8 radians relative to *La Arenosa*'s but it could be up to 1.3 radians if being accumulated from the VNG reference bus in the south-east. Although, it has not being proved yet, there seems to be a relationship between the rotor angle deviations of synchronized generators in a power system and the angle deviations of nodal voltages as suggested by the classical model of two-machine power system interconnected by a transmission line [3]-[4]-[5]. If this association was extended to security rotor angle stability criteria then the angle deviation of the nodal voltages could be used as a relative security margin, but more research is required on this.

In other words, the study case simulated for the SWPS shows that the power system is operating in a very low level of security with enough conditions to develop both a voltage stability event and a rotor angle stability event. For this study case, these two phenomena seem to be interrelated at first sight.

X. Analysis of Sensitivities

In Figure 4, additional columns are presented at the top of the diagram and above the power injections. They represent the active and reactive power sensitivities at any candidate node for new power injection, with respect to the whole system voltage profile. If any of these sensitivities is high means that new power injection at this specific node is very effective for raising the system voltage profile. On the contrary, if the sensitivity at one point is low means it is not worthwhile installing new generation at that point if the objective is to increase the system voltage profile.

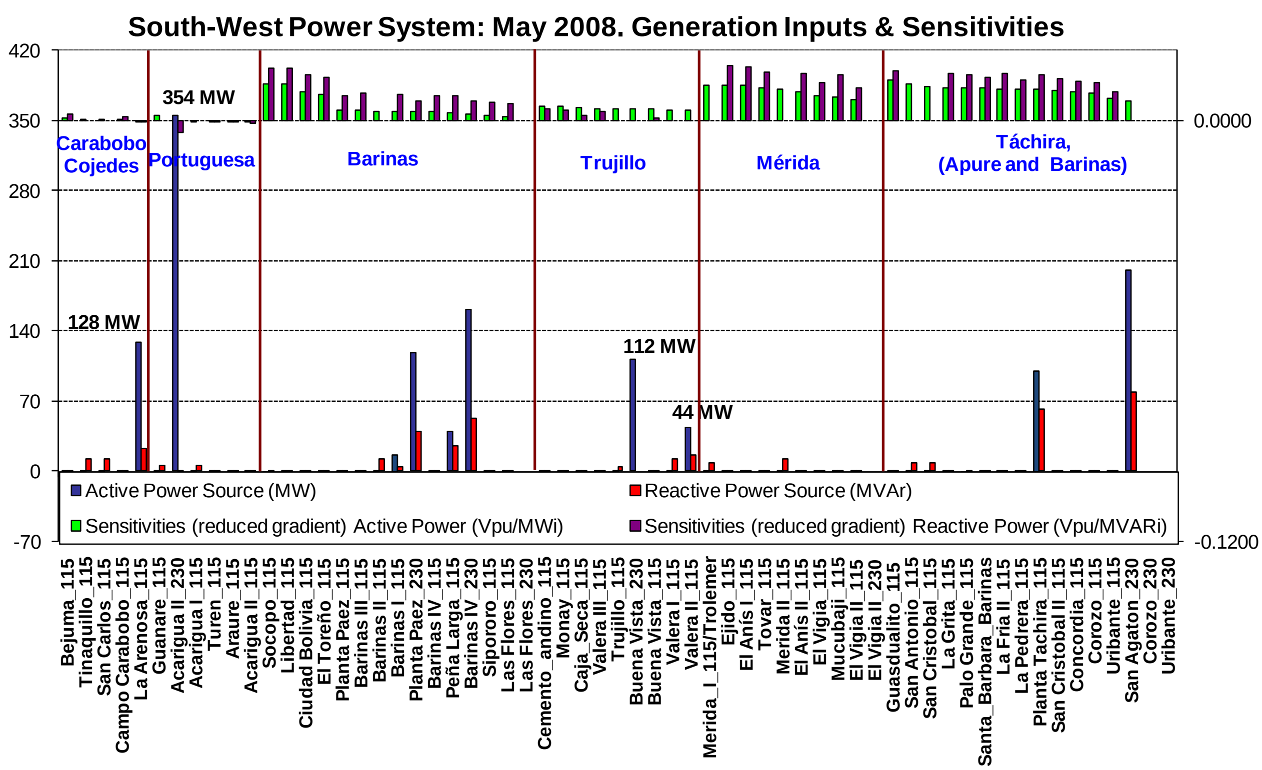

Fig. 4: Power injections and sensitivities to generation increments in the Venezuela's South-West Power System

Thus, installing new generation at any node in *Carabobo*, *Cojedes*, and *Portuguesa* states would not increase the SWPS security levels definitely. Conversely, the nodes of the rest of the regions seem to be good candidates.

Planners must study these signals carefully since in the study case of Figure 4, the reactive power sensitivities are relatively higher than those for active power at some nodes, driving them to choose a less-costly reactive compensation solution instead of new power injection. However, the big angle deviation gap is a good argument to justify the installation of rotating reactive power sources. Besides, it does not look very consistent to compare directly the sensitivities values for active power to those for reactive power. The comparison is only valid among signals of the same type. Remember that being the SWPS near the voltage collapse, the local signals for reactive compensation should be triggered.

The process for defining the systemic solution starts choosing the node with the highest signals for both reactive and active power as candidate for installing new generation. Those nodes in the study case are either *Guasdualito* or *Santa Bárbara*, the latter with better fuel logistics though. Opening the generation offer at this node, *THOR*'s OPF can define the exact power that should be injected considering the restrictions in substations and lines capacities and meeting the DG arrays particularities.

With 30 MW injected in *Santa Bárbara*, all signals for new power injection in *Táchira* state vanish but remain in *Mérida*, *Trujillo* and *Barinas* in such descending order. Again, new sensitivities must be analysed progressively to find the next generating node until completing the solution

XI. Solution

The final solution for new power injections in SWPS is presented in Table 1. The nominal capacity and power factor recommended for the new generating plants is indicated.

TABLE I

Optimum Combination of Distributed Generation Installation

Node	*Installed Power (MW)*	*Power Factor*
Sta. Bárbara	30	0.99
El Anís I	45	0.80
El Anís II	36	0.97
Monay	30	0.80

A total of 141 MW should be installed in DG equipment only at *Santa Bárbara* in *Barina*s State, *El Anis I-II* in *Mérida* State, and *Monay* in *Trujillo* State to raise the whole SWPS voltage profile. This would increase the VNG Security Margin until the new permanent infrastructure is completed.

The effects of these new power injections can be seen in Figure 5. With the exception of two radial nodes in *Barinas* State where local solutions can be applied (static compensation), all the nodal voltages in the SWPS are in the ±5% secure range.

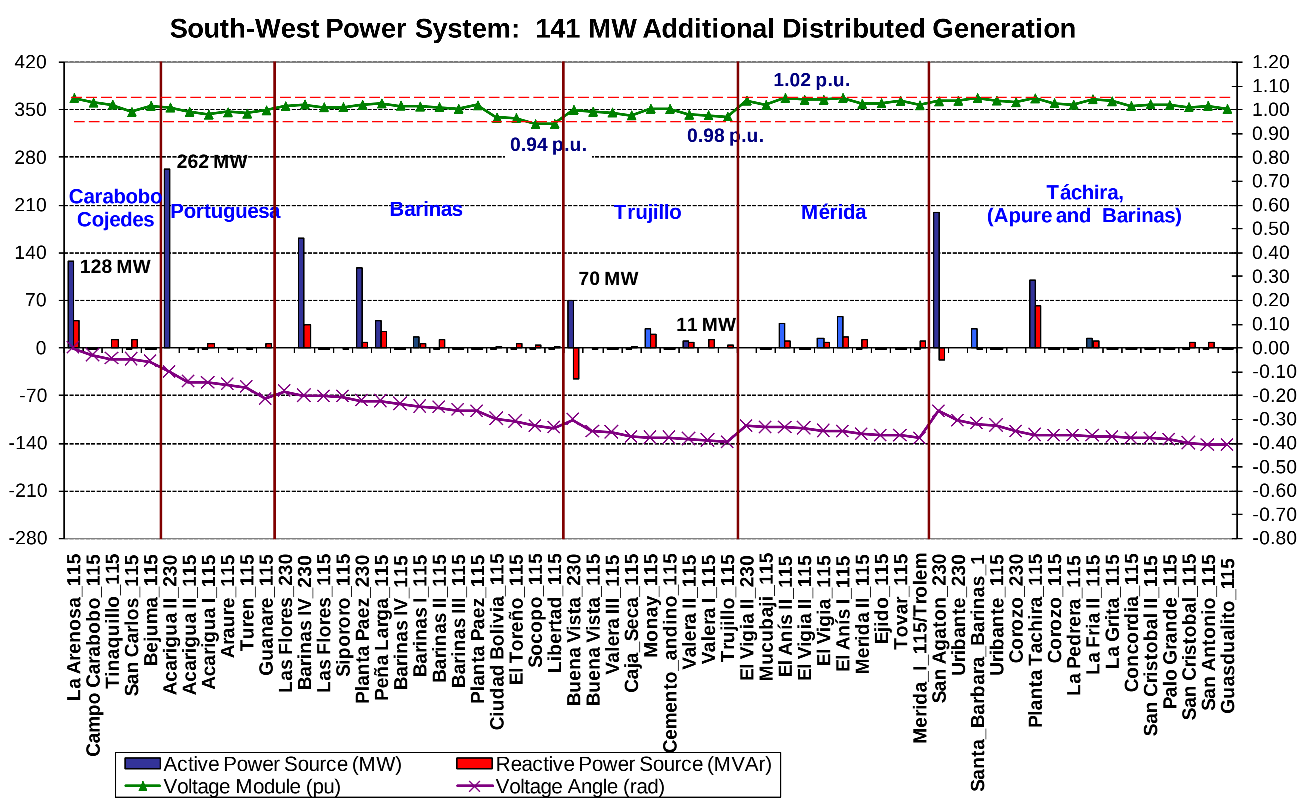

Fig. 5: Power injections, voltage profiles and phase angle deviation at the nodes of the Venezuela's South-West Power System after simulating the solution

Surprisingly, the maximum angle deviation of the nodal voltages is reduced with the new power injections in 0.4 radians, that is, half of the initial conditions value

XII. CONCLUSION

A method for designing optimal solutions for voltage stability problems analysing sensitivities was presented. It starts from the fact that a voltage profile out of the secure range criteria could drive the system to the voltage collapse therefore on fixing the voltage profile, security margin would increase. The South-West Power System of the Venezuelan National Grid was studied, revealing the presence of conditions to develop a voltage collapse event, but only with the injection of 141 MW distributed in 4 nodes, the voltage profile would rise to normal values, all without investment in new transmission lines.

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XIV. BIOGRAPHIES

Gilberto Barreto-Mederico was born in El Palmar, Bolivar State, Venezuela. He obtained a BSc in Electrical Engineering from The University Simón Bolívar, Caracas in 1980. Currently, he works for the Foundation for the Development of Electrical Service (FUNDELEC) in Caracas, Venezuela as Supervisor of Economic and Financial Studies.He has accumulated an important experience in the developing of specialised software for the coordination of hydro-thermal generation but his work has been focused recently on the optimisation topics applied on power systems. He is a researcher in the project *THOR* for the developing for a new Methodology for the Conjoined Optimal Generation and Transmission Expansion of the National Grid

Elena Caraballo-Henríquez was born in Caracas, Venezuela. She obtained a BSc in Electrical Engineering from the University of Carabobo, Valencia, Venezuela, in 1994

She works as analyst of the Economic and Financial Studies division of the Foundation for the Development of Electrical Service (FUNDELEC) and has been involved in different power system analysis. She is presently pursuing the MSc degree in Power Systems at the Central University of Venezuela, researching on voltage stability

Carlos Goyo-Barrientos (M'1997) was born in Duaca, Venezuela. He graduated from the Polytechnic University Institute of Barquisimeto, Venezuela in Electrical Engineering. Later, he obtained a MSc in Power Systems from UNEXPO, Barquisimeto in 1993 and completed his PhD degree in 2000 in UMIST, Manchester, UK.

Since 2006, he has been with the Foundation for the Development of the Electrical Service (FUNDELEC) in Caracas, Venezuela, where works in different topics including research for a new Methodology for the Conjoined Optimal Generation and Transmission Expansion of the National Grid (Project *THOR*). His areas of interest are power system planning, power system stability, distributed resources, load management, and distribution planning