Evaluation of Reactive Power Compensations for the Phase I of Paraguaná Wind based on System Voltages

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***Abstract*—The Phase I of Paraguaná wind farm is designed to provide 32.4MW to the Paraguaná power system using 24 MADE AE-61 wind turbines. This generation unit uses single cage induction generator which requires reactive power support during the power production. Three type of dynamic reactive power compensation are evaluated in this paper: Mechanically-switch shunt capacitor, static var compensator and static synchronous compensator (STATCOM). Time-domain simulations using DIgSILENT® PowerFactory™ over the Paraguaná power system are used to evaluate the dynamic behavior of bus voltages during and after a three-phase fault. Results demonstrate STATCOM provides the best reactive power support to the network to compensate the large amount of reactive power absorbed by the wind turbine after fault and thus they considerably improve the recovery of system voltages.**

Keywords*— Electric power system, power system dynamic, wind power generation, wind power integration

I. INTRODUCTION

Bolivarian Republic of Venezuela has a long history of interest in developing Renewable Energy Sources (RES) [1]. The Venezuelan Ministry of Electricity and Energy (MEE) is committed provide all the support in order the Venezuelan Electrical System meet the commitments arising from the Kyoto Protocol [1], [2]. Several projects have been promoted by the MEE to promote renewable energy sources installations, it included five wind farms on the archipelagoes and islands of Los Roques, Los Monjes, La Ochila, La Blanquilla and La Tortuga Island [3]. In addition to these projects three wind farms, of utility scale, are presently under development in mainland Venezuela, in La Guajira, Paraguaná peninsula and Margarita Island [1], [3]-[4].

Although a wind atlas is not currently available for Venezuela, relevant literature [2], [4] has identified some preliminary areas suitable for wind energy projects, such as [4]: (i) Paraguaná peninsula and Santa Cruz de los Taques (or Los Taques as known) (ii) La Guajira area in Zulia state, and (iii) Margarita Island. The project of Paraguaná wind farm consider two phases for a total of 100 MW installed capacity (see Fig. 1). This wind farm is expected to install 76 generation units, 1320 kW each, MADE AE-61. It consists of *fixed speed wind turbine* (FSWT), stall regulated, with *single cage induction generator* (SCIG). This generation technology consumes reactive power, and therefore voltage problem caused by the lack of reactive power is serious.

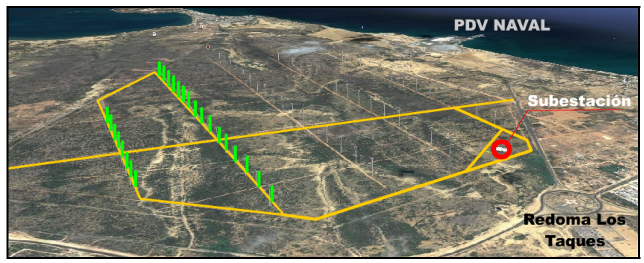

Fig. 1. Schematic representation of Paraguaná wind farm, the Phase I: 24 wind turbines highlighted in green color.

The integration of the Paraguaná wind farm has several implications on voltage control and reactive power support of Paraguaná Power System. It may results in voltage variations outside the regulation limits, flicker violations. These problematic situations have been discussed in several publications [5], [6], [7]. Several solutions have been proposed to improve the voltage control, voltage stability and reactive power support on wind farm based on fixed speed wind turbines (FSWT): (i) *mechanically-switch shunt capacitor* (MSSC) [8], (ii) *static var compensator* (SVC) [9] and (iii) *static synchronous compensator* (STATCOM) [10].

The objective of this paper is to present results of a preliminary evaluation of dynamic reactive power compensations for the integration of Paraguaná wind farm; it is based on system voltages. This paper considers only the integration of the Phase I of Paraguaná wind farm, 24×1.32kW and three types of reactive compensation equipment are considered in this paper: MSSC, SVC and STATCOM. All the data used for simulations purposes is publically available.

The structure of this paper is a follow. Section II describes briefly the Paraguaná power system and the wind farm characteristics to be integrated whilst Section III presents the results obtained are discussed by emphasizing their significance. The main contribution of this paper demonstrates STATCOM provides the best reactive power support to the network to compensate the large amount of reactive power absorbed by the wind turbine after fault and thus they considerably improve the recovery of system voltages. A

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preliminary evaluation about the changes on the short circuit levels indicates low impact on the power quality is expected for the Phase I of Paraguaná wind farm, but potential detriment on power quality can be caused when the Phase II (100MW) is completely installed. Further evaluations are required for the Phase II. The conclusions of this paper are presented on Section IV.

II. Study Case

A. Paraguaná's Power System

Venezuela's power system is an integrated vertical power company, called *Corporación Electrica Nacional* (Corpoelec) which covers most of the country. The Paraguaná Peninsula transmission system is fed from a double circuit overhead transmission (230kV) of San Isidro substation as part of the Venezuelan power system. Fig. 2 shows all substations, transmissions lines, static reactive compensators, and generators of the Paraguaná's power system. There are several power plants in the area: Planta Coro II, Josefa Camejo, Genevapca and several distributed generation (DG) units.

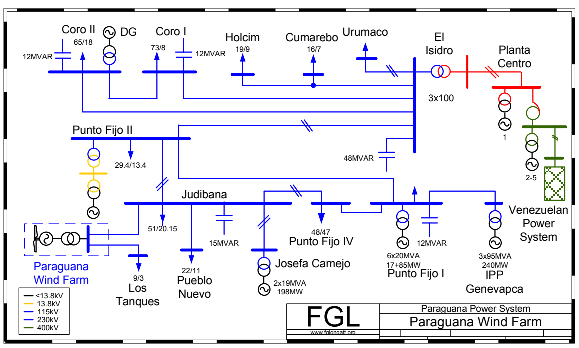


Fig. 2. Representative one-line diagram of the Paraguaná Power System.

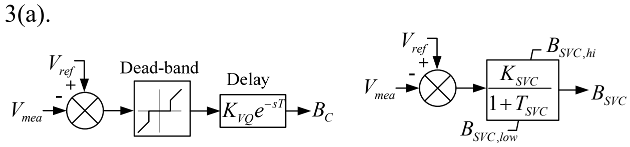
The local generation covers only a part of the total demand; the overhead transmission lines El Isidro-Planta Centro import the remaining power from the Venezuelan Power System. Fig 3 shows the typical hourly generation-demand balance on the Paraguaná power system, heavy load power transfer on the interconnection transmission lines show how positive will be the integration of the Paraguaná wind farm in terms of local generation.

B. Paraguaná Wind Farm

The 100 MW Paraguaná wind farm is currently under construction and the Phase I has been already installed and is under electro-mechanical tests at the time this paper is written. It is located between populations of Amuay and Los Taques in the state of Falcon (*Estado Falcón*). The Phase I is designed to provide 32.4MW using 24 MADE AE-61 wind turbines with an approximate height of 70 meters per unit. The wind farm will be connected with two overhead transmission lines, 115kV: Los Taques-Paraguana wind farm (1km) and Judibana-Paraguaná wind farm (9km). The MADE AE-61 consists of FSWT, stall regulated, with SCIG at 690 V. Individual step-up transformer (0.60/34.5 kV, 1.6MVA) and static compensation of reactive power (630 kVAr) is located in each turbine. Four underground feeders (34.5kV) are used to collect the power generated by wind turbines and a step-up substation (34.5/115 kV) transmits the power generated into the Venezuelan power system.

C. Reactive Compensation

Passive reactive power compensation devices like MSSCs are modeled as admittance elements, however, specials models are required for SVC and STATCOM [11], [12], [13]. The main objective of the control system is to determine the reactive power device susceptance (B) needed in the point of connection to the power system, in order to keep the system voltage close to some desired value. The dynamic model for tap changing MSSC includes a dead-band and time delay with voltage sensitive proportional controller, it is depicted on Fig 3(a).



(a) Switched capacitor controller (b) SVC controller

Fig. 3. Simplified model for reactive power compensation devices

Several models adequate for general propose dynamic studies has been prepared by IEEE [12]. In this paper, a simple limited-first order transfer function is used, it is depicted on Fig 3(b) [14]. A proportional-integral control scheme is used to define the reference currents on *dq* axis, and is used to control the STATCOM [12] and it is depicted on Fig. 4.

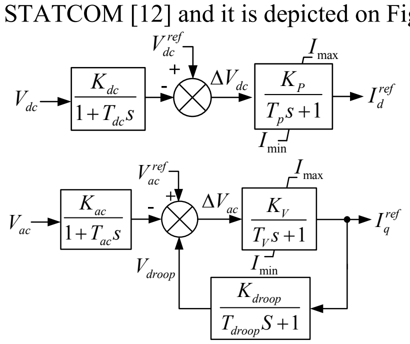


Fig. 4. Simplified model of STATCOM controller.

D. Wind Turbine

Fig. 5 depicts the general structure of a FSWT with a SCIG, various subsystems are included, all of them are modeled in this paper [5], [15], [16].

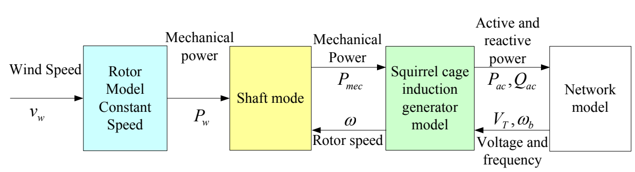


Fig. 5. General structure of a model of a FSWT with SCIG [16].

III. Simulation and Results

The integration of Paraguaná wind farm into the Paraguaná power system leads to changes on reactive power flow and bus voltages. The assessments of these changes are necessary for the operation and control and to define some potential system reinforcements. This section presents the main simulations and results analyses about reactive power compensation alternatives for the Phase I of Paraguaná wind farm (32.4MW). Time-domain simulations are performed using DIgSILENT® PowerFactory™ [17] and the dynamic models are created by the author using *DIgSILENT Simulation Language* (DSL). A preliminary evaluation about the reactive power requirements during the steady-state operation of the Paraguaná wind farm is performed and results are shown of Fig 6.

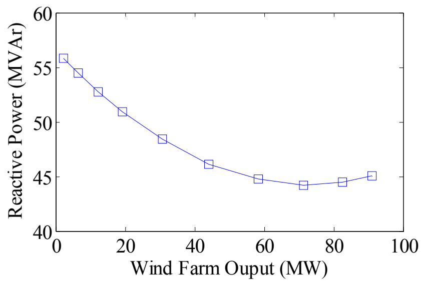


Fig. 6. Steady-state reactive power requirements on the Paraguaná wind farm (Phase I and II) to keep the PCC voltage at 1.00 p.u.

Fig 6 shows the reactive power consumption of the wind farm is a function of its power production and increases as the active power output increases. Low active power production requires more reactive power compensation (Q_c) and the minimum compensation is required around 75MW, (44.23MVar). These preliminary reactive power requirements are partially covered by fixed shunt-capacitors installed at the generator terminals (630 kVAr), however, any reactive power consumption in excess during the wind farm operation, must be compensated by other means. The active power production is changing as consequence of wind speed changes as consequence more dynamic changes on the reactive power compensation are expected and dynamic reactive power compensation is required.

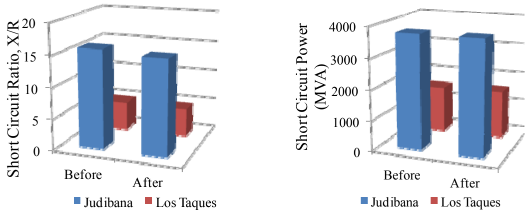


Fig. 7. Short Circuit Levels at Los Taques and Judibana Substation on the Paraguaná power System, considering the integration Phase I of Paraguaná wind farm.

The integration of Paraguaná wind farm increases short circuit levels on local power system and decreases the *X/R* ration, Fig. 7 shows these changes on Los Taques and Judibana substations. Low impact on the power quality is expected for the Phase I of Paraguaná wind farm, however, the fault levels of the grid indicates some detriment on power quality can be caused when the Phase II is completely installed. Three types of reactive power compensation: MSSC, SVC and STATCOM devices are evaluated in this paper. The individual sizing and setup of all parameters involved in these models are beyond the paper's scope. However, some practical guidelines for preliminary studies have been considered in this paper [12].

All the reactive power controllers are settled for minimal time lag compared with the voltage regulators and power system stabilizers on the Paraguaná power system. Dynamic reactive power compensation may be used to damp electro-mechanical oscillation; it has been extensively reported on the literature. However, there is not any reported evidence about inter-area oscillation in the Venezuelan electric power system, as consequence, controllers of reactive power devices are designed for local compensation.

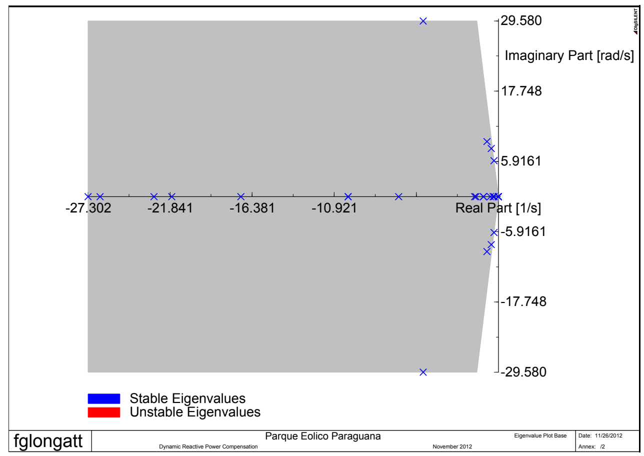


Fig. 8. Plot of the main electromechanical eigen-values of Paraguaná power system.

Fig 8 shows a plot of the main electromechanical eigen-values on the Paraguaná power system. MSSC has not effect of dynamic model of Paraguaná power system. SVC and STATCOM increases the order of the dynamic model in two and three respectively and these devices have a positive effect on local small signal stability, increases the damping ratio and reduces the frequency oscillation.

A three-phase short-circuit (X_f=4.0Ω) at Punto Fijo II-Judibana overhead transmission line (115kV) is used as disturbance in this paper to evaluate the performance of the dynamic reactive power compensation. This fault produces the worst case voltage dip on transmission system used to connect the Paraguaná wind farm. *Fixed compensation capacitor* (FCC) is considered at wind turbine terminal for a total reactive power of 15.12 MVAr. However, the reactive power production is a function square of the voltage, which means the effective compensation, is only 13.90MVAr at operation voltage. The dynamic behavior of bus voltages (V) on the Paraguaná power system and the main variables of the wind farm: reactive power consumption (Q_g) and reactive power compensation (Q_c). Fig 10 shows the results considering the integration of Paraguaná wind farm without an additional reactive compensation device (see Fig. 9). The FCC installed at the wind turbines cannot provide dynamic compensation for the sort circuit event considered, the sudden drop of voltage reduces effective reactive power compensation to 820kVAr when the fault is cleared. Slow voltage recovery is evident on all bus after the fault and it is special slow on the wind turbines terminals affecting the active power production. Post disturbance voltages at El Isidro 230 and 115 kV busbar are low (0.938 p.u and 0.924 @ 1.00sec) as consequence of the changes on the power pots-contingency (~70MW lost on Punto Fijo II-Judibana transmission line).

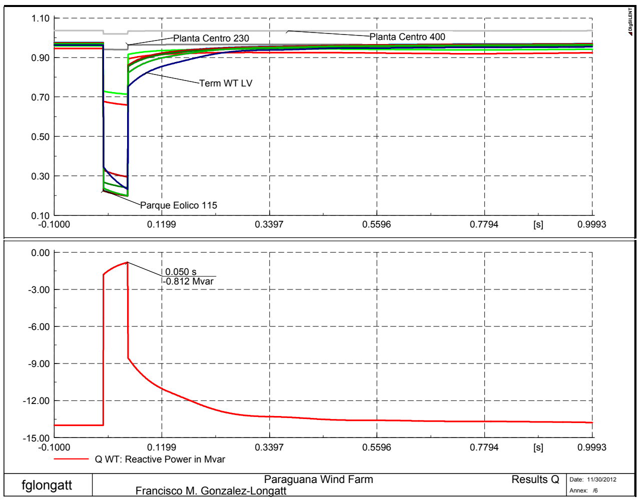


Fig. 9. Simulation Results: Base Case.

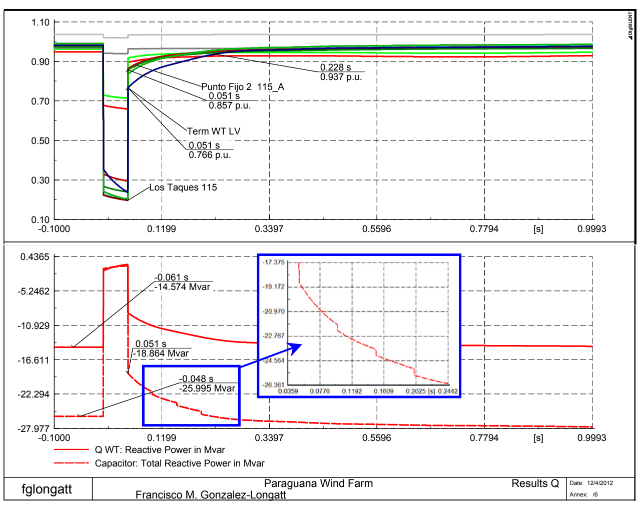


Fig. 10. Simulation Results: Mechanically-switched capacitor.

A. Mechanically-Switched Shunt Capacitors

Slow reactive power variations in reactive power are controlled using MSCC. However, the performance of this device on fast reactive power changes together with sudden drop of voltage, as considered disturbance, is a complicated situation. Fig. 10 shows the results considering a reactive compensation based on MSCC. During faults conditions the reactive power production of MSCC system is dramatically reduced because its output is decreased with the square of the voltage [18]. After disturbance the switch controller acts and helps on the voltage recovery process. MSSC produces an improvement on the local voltage profile, however, voltage profile inside the wind farm is very low inside and the effectiveness of the fixed capacitor installed on the terminal of wind turbines is affected.

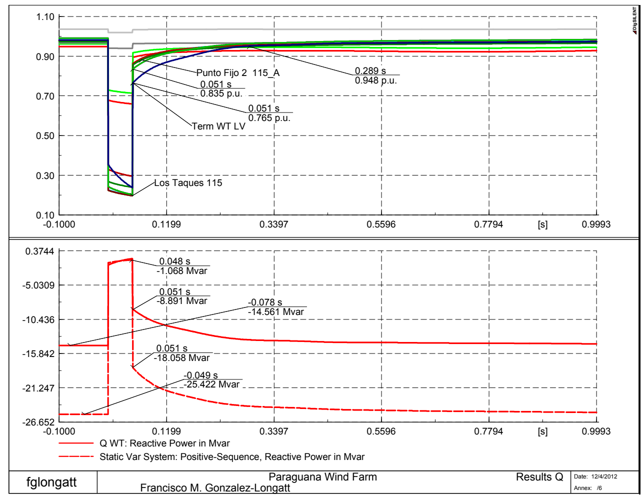


Fig. 11. Simulation Results: SVC.

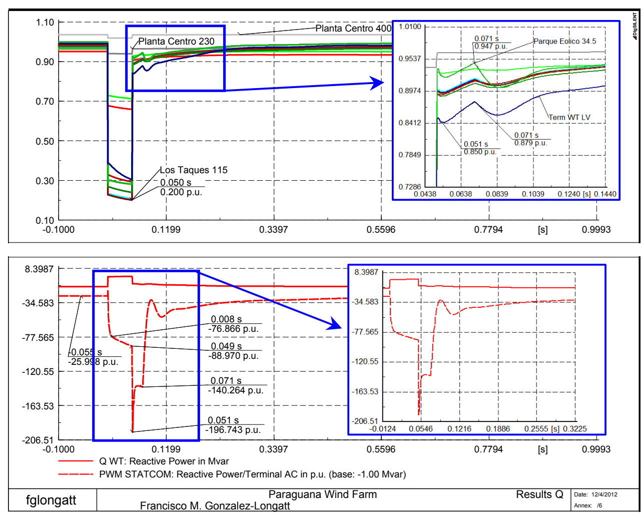


Fig. 12. Simulation Results: STATCOM.

B. SVC

The dynamic response of Paraguaná power system considering a SVC is shown on Fig 11. The SVC allows rapid changes on reactive power production which improves the post-fault voltage recovery. This effect is notoriously positive on the Paraguaná power system. The gain and time constant settings on SVC controller are based on the system short circuit capacity; however, during fault condition the reactive power production is not enough to provide a voltage support.

C. STATCOM

Fig. 12 shows the dynamic response of Paraguaná power system considering a STATCOM. The STATCOM is a voltage-source converter that behaves like a source of reactive power during the fault condition providing low voltage fault through. Reactive power production is sensible increased during the fault time period because the short-time overload capabilities on the STATCOM. However, output is a linear function of the voltage, as consequence, the reactive power decreases linearly with the voltage since they are constant current controllers. The recovery period on the after-fault local bus-bar voltages on the Paraguaná power system have a slightly un-damped behavior. The fast controller and the over-load characteristics of this device provide an excellent performance.

A. Summary

A comparison of the dynamic performance features for the three reactive power compensator considered is shown on Table II.

TABLE I. COMPARISON OF THE DYNAMIC PERFORMANCE OF THE REACTIVE POWER COMPENSATIONS

Case	*Overshoot*	*Settling time*	*Voltage during the fault*	*System performance*
MSCC	No (0)	High (~1sec)	Very Low (~0.20 p.u)	Unacceptable
SVC	No (0)	High (~0.98sec)	Very Low (~0.20 p.u)	Unacceptable
STATCOM	High (67%)	Low (~0.48sec)	Medium (~0.40 p.u)	Good

IV. CONCLUSIONS

The dynamic behavior of the Paraguná power system voltages considering the integration of the Phase I of Paraguaná wind farm has been investigated in this paper. The transient performances of this wind farm equipped with MSSC, SVC, and STATCOM, has been studied and the result shows: (i) SVC and STATCOM can provide reactive power support to the network to compensate the large amount of reactive power absorbed by the FSWT using SCIG after fault and thus they considerably improve the recovery of system voltages, (ii) STATCOM has better capability for providing reactive power compensation during low AC voltage than SVC. Therefore, system with a STATCOM is less likely to become unstable than system with a SVC, (iii) The increase in ratings of SVC/STATCOM will provide better reactive power support to the network and improve the system voltages recovery. Further evaluations are required about the integration of Phase II.

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