Impact of a 47 MVA Aeroderivative Gas Turbine Generator on a 346 MW Bulk Wind Farm – Case Study on Voltage & Frequency Response

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***Abstract*— This paper demonstrates the impact of a single GE LM2500XPRESS* Aeroderivative gas turbine generator (GTG), when operated in parallel with a bulk wind power plant, with regards to the latter's power transfer capacity, by providing the necessary voltage and reactive power support at the point of interconnection (POI). The hybrid application also improves the transient voltage response during large disturbances at the POI. It further demonstrates the GTG's positive impact on the network frequency profile during short-term load adjustment and loss of generation events.**

Keywords—grid firming, aeroderivative, wind turbine generator, ancillary services, voltage, frequency

I. Introduction

The global energy system is transforming at a scale and pace never experienced before. Bulk wind farms are of the one of the most popular sources of renewable energy. Throughout the world, and particularly in North America and Europe, bulk wind farm penetration has increased dramatically. As more and more renewables come into play, grid operators and regulators are faced with significant operational challenges. Integrating intermittent renewables and distributed energy resources into an aging grid requires flexible and resilient technologies, able to ramp up or down rapidly and dynamically adjust to real-time grid signals. The declining cost of renewables enabled the addition of a substantial amount of renewable assets on certain grids. Several regions have already exceeded 30% of renewables installed capacity on the grid, such as California, as well as many European countries, while others are aiming at aggressive targets by 2050 to reach 100% renewable portfolio standard independent of fossil fuel such as Denmark. While these figures signal the depth of the renewables penetration, it should be noted that for some regions like ERCOT, in Texas, in some occurrences, the instantaneous wind generation recorded even a higher value (48.3%) of the electricity demand on March 23, 2016 [1]. These grids are facing several challenges to integrate all these renewable energy sources into the grid, and among those challenges:

1) A need for Spinning Reserve sources to firm the capacity and balance the demand to counteract the variability of wind and solar.
2) Lack of rotational/synchronous inertia back to grid leading to frequency deviations and hindering the system to recover rapidly from contingencies.
3) The power electronics tend to weaken the grid with lower short circuit ratio.
4) The ancillary services that include frequency and voltage regulations to support grid stability become a necessity.
5) Voltage ride through contingencies.

The rise of the need for ancillary services to address intermittent renewable resources shortfalls include, but are not limited to: (a) Primary Frequency Response (b) AGC Regulation (c) Load Following (d) Spinning Reserve (e) Non-spinning Reserve (f) Replacement Reserve (g) Reactive Power/Voltage Support, and (h) Black Start.

Some traditional methods of voltage control in a power system are: (a) by adjusting the generator excitation (b) using shunt capacitors (c) using series capacitors (d) synchronous capacitors, i.e. motors (e) auto tap changing transformers (f) regulating and boosting transformers [2]. However, thermal hybrids are gaining popularity to address the grid firming challenges. This paper focuses on the impact of a single GE LM2500XPRESS 47.8MVA GE Aeroderivative gas turbine generator (GTG) package when installed and operated in parallel with 346.5MW bulk wind farm for the purposes of grid firming, specifically with regards to the voltage response and reactive power support at the point of interconnection (POI). It also investigates the GTG's impact on the network frequency profile during short-term load adjustment cases. The LM2500XPRESS is compact, fast start (5 minutes) and cyclable without life impact, and is capable of delivering/consuming reactive power that is required to maintain voltages with acceptable limits at the POI, as well as responding to real power demands during network frequency excursions when necessary.

II. Wind Turbine Generator Model

The application of wind turbine generators (WTGs) in modern wind power plants (WPPs) requires an understanding of a number of different aspects related to the design and capabilities of the machine involved. A wind turbine consists of a rotor, generator, blades, and a driver of coupling device. As such, the WTGs can be categorized into five (5) different types,

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as shown in Table I below. Earlier models of WTGs (Types 1 and 2) were relatively simple machines that consumed reactive power in order to produce real power. Although WTGs do not produce any CO_2 or pollutants, they have three major drawbacks [3]:

1) output cannot be controlled

2) WPPs are mostly suited for peaking applications

3) power is produced only when there is sufficient wind.

TABLE I. TYPES OF WTGs

	Speed	**Power Electronics**	**Voltage Control Capability**	**Reactive Power Capability**
Type 1	Nearly Fixed	None	None	Only via PFCC*
Type 2	Limited Variable	None	None	Only via PFCC*
Type 3	Variable	Partial	Yes	-0.9 to +0.95
Type 4	Variable	Full	Yes	-0.9 to +0.95
Type 5	Variable	Full	Yes	-0.9 to +0.95

*PFCC: Power Factor Correction Capacitor

A "pseudo case" has been developed, based on the 300MW WPP located in Prairie Hill, Texas. The actual WPP consists of 100 – 3MW ACCIONA AW3000 WTGs, without the LM2500XPRESS GTG. For modeling and study purposes, ACCIONA's AW3465 WTGs (the largest available – 3.465MW) was chosen, in order to scale up the WPP model to 346.5MW rated capacity. Ambient condition of 35 degree C was chosen for analysis. At 35 degree C, AW3465 is rated for 3.465MW at +/-98.5% power factor (+/-600kVAR). It is a 6-pole machine, with rated slip and speed of 20% and 1440rpm, respectively. The sub-transient, transient and synchronous reactance ratings are considered to be approximately 20%, 23% and 400% respectively. The corresponding time constants are considered to be approximately 68ms, 78ms and 1.13s [4]. AW3465 WTGs consist of a 3-phase Doubly Fed Induction Generator (DFIG), where a small amount of power injected into the rotor circuit can affect a large control of power in the stator circuit [3]. In addition to the real power that is delivered to the grid from the generator's stator circuit, power is delivered to the grid through the grid-connected inverter when the generator is moving faster than synchronous speed [3]. When the generator is moving slower than synchronous speed, real power flows from the grid, through both converters, and from rotor to stator [3]. When it comes to the reactive power control, typically there is no compensation provided to the WPP owners, if they supply reactive power to the grid [5]. Therefore, the reactive power supplied to the grid is typically zero under normal steady-state conditions [5]. However, the WPP may export reactive power under lower AC system voltage conditions [5]. In order to meet Low Voltage ride Through codes, the converter might supply reactive power during a fault [5].

III. GAS TURBINE GENERATOR MODEL

GE's LM2500XPRESS Aeroderivative gas turbine coupled with ANDRITZ A03OP-T generator has been considered for modeling and study purposes. The output of the GTG was set at 30MW (35 degree C). At 35 degree C, LM2500XPRESS is rated for 30MW at 80% power factor. It is a multi-shaft 2-pole machine, with rated speed of 3600rpm, respectively. The sub-transient, transient and synchronous reactance ratings are considered to be approximately 16%, 23% and 230% respectively. The corresponding time constants are considered to be approximately 20ms, 700ms and 7.2s . Additionally, the LM2500XPRESS is equipped with synchronous condensing capabilities, such that the unit can deliver up to 40MVAR and consume up to 16MVAR of reactive power [6]. Total turbine-generator drive train inertia (H) constant is considered to be 1.375.

IV. THE HYBRID ARRANGEMENT & STUDY METHODOLOGY

Figure 1 below shows the hybrid arrangement of LM2500XPRESS 40MW rated GTG installed and operated in parallel with a WPP rated to deliver 346.5MW to the bulk power system. Generator Step Up Transformers Tap positions have been fixed at Nominal for all cases, and therefore the impact (if any) of the On-Load Tap Changers are not considered. The WPP and GTG are connected to a fictitious network comprising of a 240kV grid (acting as the "swing" bus with assumed strength of 5kA), 100-mile long transmission line, and lumped load of 500MVA at 80% power factor served by the network. The 240kV grid is represented as Thevenin equivalent with voltage in series with reactance. The GTG 13.8kV bus is set to Voltage Control mode to maintain 1.0 per unit voltage, while the Exciter and Governor models of the GTG are Fixed. The Power System Stabilizer function of the GTG is turned OFF. The WTG 12kV bus is also set to Voltage Control mode. All buses set at 1.0 per unit voltage. No additional PF and/or VAR control/support available. For the purposes of frequency response evaluation, WPP penetration (Type 4) is considered to be at approximately 25% of the total generation sources, the GTG governor droop is set at 5% on the standard GGOV1 model, and the grid (swing bus) is represented as equivalent synchronous machine with GGOV3 governor model and H constant of 5.

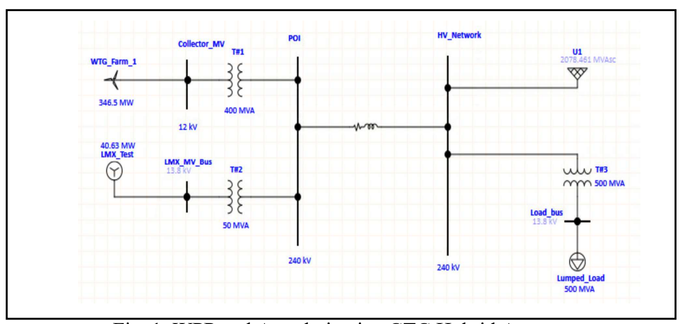

Fig. 1. WPP and Aeroderivative GTG Hybrid Arrangement

Voltage security is the ability of a system to operate in a stable mode and to remain stable following credible contingencies or load increases. It often means that the existence of considerable margin from an operating point to the voltage instability point involves credible contingencies. Voltage stability has often been viewed as a steady-state viability problem suitable for static analysis techniques. The ability to transfer reactive power from production sources to consumption sinks during steady operating conditions is a major aspect of voltage stability [7]. On the other hand, frequency stability is the ability to maintain frequency within acceptable nominal range by ensuring generation-load balance.

A. Steady-State Response

1) Establish the WPP's steady-state MW transfer capability limits (vs POI Voltage), without any reactive power production at the WPP. This is considered the Base Case.

2) Examine the impact of LM2500XPRESS GTG operating in "Synchronous Condensing" mode on the Base Case from step 1. GTG Output is set at 0 MW.

3) Examine the impact of LM2500XPRESS GTG operating in "Power Generating" mode on the Base Case from step 1. GTG output is set at 30MW, keeping the overall "hybrid" output profile consistent with step 2. This is done by correspondingly adjusting the WPP output.

4) Repeat steps 1 to 3, with total WPP reactive power limit increased to +/- 60MVAR (from 0 MVAR).

B. Transient Response

1) In the Base Case, at 90% WPP output, a 3-ph fault is placed at the HV Network at 1.0 seconds and cleared at 1.15 seconds. Obtain the resulting transient voltage response at the POI.

2) Examine the impact of LM2500XPRESS GTG operating in "Synchronous Condensing" mode on the Base Case from step 1. GTG Output is set at 0 MW.

3) Repeat steps 1 to 2, with total WPP reactive power limit increased to +/- 60MVAR (from 0 MVAR).

C. Frequency Response

1) In the Base Case, i.e. without GTG in-service, arbitrarily apply +/- 2.5% load ramp over 5 seconds.

2) Observe the resulting network frequency profile.

3) Repeat the above steps with GTG in-service.

V. Results and Summary

For the steady-state cases, the LM2500XPRESS GTG operated in two different modes – Synchronous Condensing and Power Producing. In both cases, the impact of the GTG dramatically increases when the WPP is operating at greater than 50% of its rated capacity. In the base case, the GTG helped increase the MW transfer capacity of the WPP by up to ~30%, while augmenting the voltage at the POI by 15-90% (refer to Figures 2 and 4). In the case where WPP produces 60MVAR of reactive power, the GTG augmented the POI voltage by ~5% (refer to Figures 3 and 5). Additionally, the normalized gross output of the hybrid arrangement yielded even better results with regards to MW transfer versus POI voltage. For the transient cases, the GTG operated in Synchronous Condensing mode. This provides adequate damping by limiting the first-swing transient voltage overshoot by ~15-40%. Refer to Figures 6 and 7. In the case of frequency response evaluations, noticeable improvement was found with GTG in-service, both in terms of limiting the under- and over-shoot as well as the frequency recovery profiles. Refer to Figures 8 and 9. The extent of this improvement depends on many factors, mainly: (a) droop settings (b) load ramp rates (c) WPP penetration levels (d) the initial load setpoint of the GTG and (e) available MW headroom of the GTG.

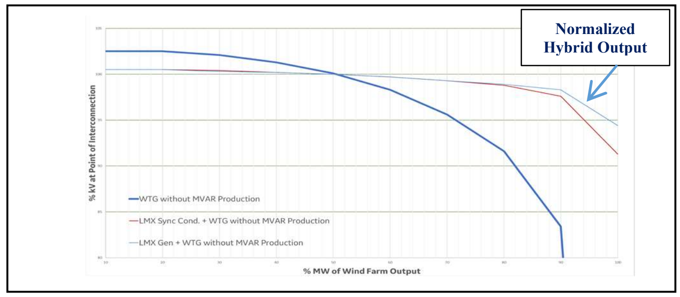

Fig. 2. WPP %MW vs %POI Voltage – Base Case

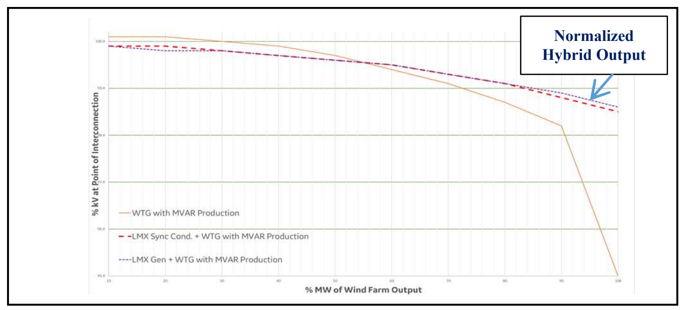

Fig. 3. WPP %MW vs %POI Voltage (with 60MVAR support from WPP)

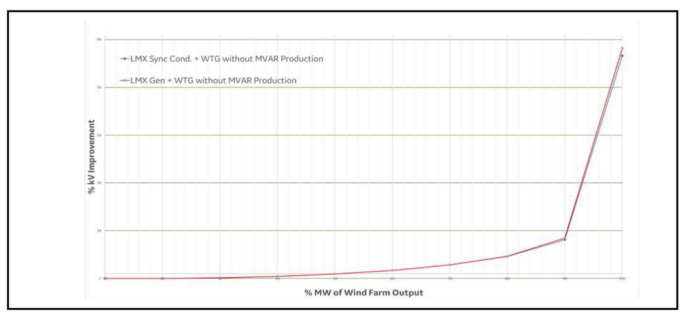

Fig. 4. WPP %MW vs %POI Voltage Improvement – Base Case

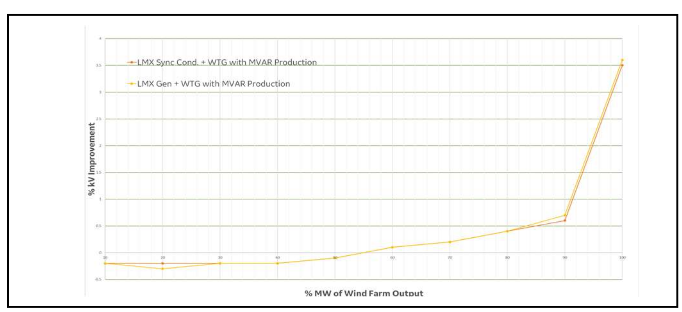

Fig. 5. WPP %MW vs %POI Voltage Improvement (with 60MVAR support from WPP)

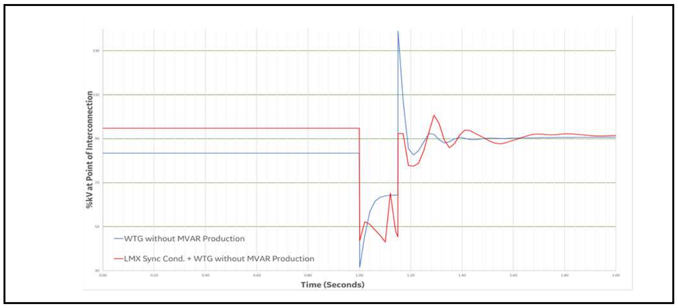

Fig. 6. Transient Voltage Response – Base Case

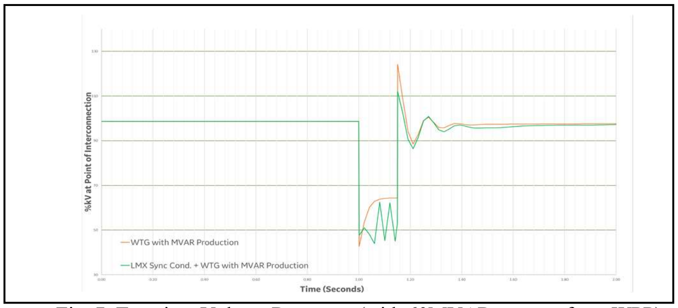

Fig. 7. Transient Voltage Response (with 60MVAR support from WPP)

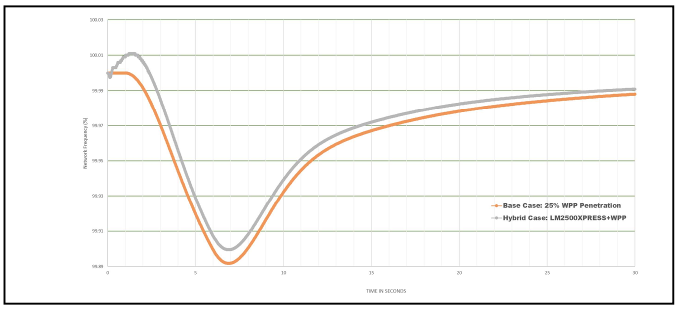

Fig. 8. Network Frequency Response to (+) 2.5% Load Ramp Over 5 seconds

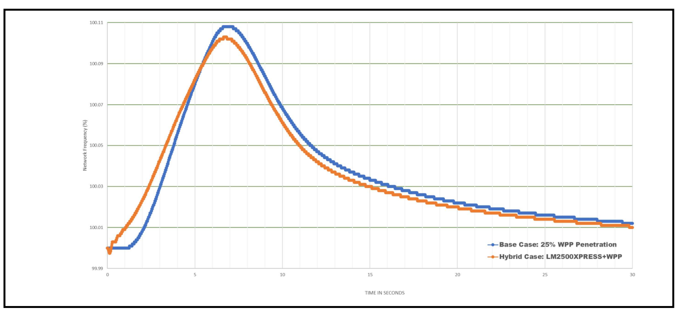

Fig. 9. Network Frequency Response to (-) 2.5% Load Ramp Over 5 seconds

The results presented in Figures 8 and 9 are further substantiated on a test system comprising of 25% WPP and 75% traditional generation, where a "chunk" of WPP (200MW) is tripped with no corresponding frequency response. The test is repeated with the "chunk" of WPP now replaced by LM2500XPRESS (10 units), with linear response ramp rate of 300kW/s. The input data is presented in Table 2, and the results are presented in Figure 10. There is noticeable improvement in frequency response in the Hybrid architecture, even without considering the initial inertial response. Given that the scope of the frequency sensitivity study is limited to 1 minute, the corresponding response characteristics is limited to Primary, i.e. Governor action only, as shown on Table 3.

TABLE II. TEST SYSTEM INPUT DATA

Parameters	Wind Only (0-60 sec)	Hybrid (0-1 sec)	Hybrid (1-60 sec)
PNR	0.25	0.25	0.25
PR	0.75	0.75	0.75
PL	1	1	1
PTRIP	2.67x10^-3	2.67x10^-3	2.67x10^-3
fn	1	1	1
a0	0	0	-4.52x10^-3
a1	0	0	4.52x10^-3
H	5	5	5
f0	1	1	1

Where [8],

PNR = Power Source (Non-responsive), in per unit

PR = Power Source (Responsive), in per unit

PL = Total Load, in per unit

PTRIP = Generation Trip, in per unit

fn = Nominal Frequency, in per unit

a0 = ramp rate constant, in per unit

a1 = ramp rate, in per unit

H = Inertia Constant, in seconds

f0 = Initial Frequency, in per unit

TABLE III. FREQUENCY RESPONSE VERSUS TIME [8]

Time Scale	Response Type
0 to 1 second	Machine Inertia/kinetic energy
1 second to 1 minute	Primary (i.e. Governor action)
Greater than 1 minute	Secondary (i.e. MW setpoint adjustment)
Greater than 10 minutes	Tertiary (i.e. Plant re-scheduling)

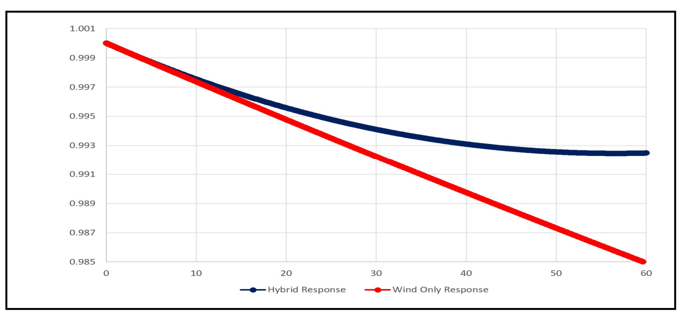

Fig. 10. Hybrid Response to Generation Loss

As demonstrated above, the detection and mitigation of voltage and frequency excursions in thermal-hybrid applications of wind farms and LM2500XPRESS can be achieved by utilizing the latter's fast start capability, as well as its flexibility to deliver/consume reactive power while simultaneously producing real power. As such, it addresses potential ancillary services gap related to voltage and frequency by proposing a thermal-hybrid architecture with real-time monitoring of the key parameters, and engaging the LM2500XPRESS as necessary, as shown on Figure 11.

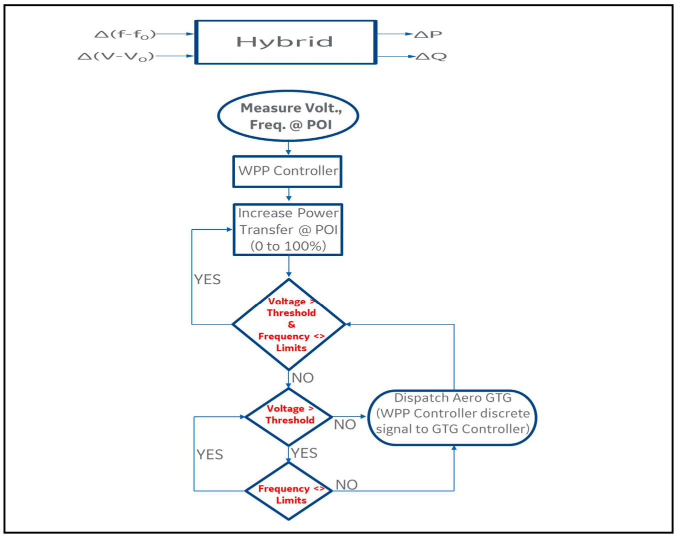

Fig. 11. Voltage and Frequency Optimization in Thermal-Hybrid Architecture consisting of LM2500XPRESS & Wind Farm

VI. Conclusion

The LM2500XPRESS GTG, when operated in Synchronous Condensing or Power Generating mode, in parallel with a WPP, improves the latter's power transfer capacity by providing the necessary voltage and reactive power support at the POI. The hybrid application also improves the transient voltage response during large disturbances at the POI. Further, during hybrid operation the GTG had a noticeable positive impact on the network frequency profiles during short-term load adjustment and loss of generation events.

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