Security of a Power System Under High Penetration of Wind Energy Considering Contingencies and Stability Margins

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***Abstract*—Security is a well-known function to any transmission operator and system planner. As the world is moving toward the decarbonization of the power industry, it is more complicated for the system operators to maintain an acceptable level of security in the power system operation. More large-scale wind farms are being incorporated into the grid, and thus, the voltage stability concern is increasing. In practice, several contingencies are imagined by the system operators to assess the reliability of the grid. Since voltage stability is one of the major menaces that can trigger voltage instability in a power system, this paper is attempting to present to the transmission system planners and operators a dedicated methodology to facilitate the incorporation of large-scale wind farms into a transmission grid under high penetration of wind power. the stability of a wind-dominated power system is discussed based on Q-V and P-V methodologies and some N-1 contingencies with the Remedial Action Schemes (RAS). Furthermore, a methodology to rank the worst contingencies and to predict the voltage collapse during the highest wind penetration level is presented. Simulations have been, extensively, carried out to examine the methodology and have provided valuable information about the static security of the wind-dominated power system. The results can be used by the transmission system operator to anticipate voltage instability or voltage collapse in the power system during high wind penetration levels.**

***Index Terms*—Generation and Transmission Planning, Contingency Analysis, Electric Grid Resiliency and Reliability, Renewable Energy Sources**

I. Introduction

Due to the climate change menace, today's landscape of the traditional power system is subjected to tremendous changes [1]. At the same time, the power system is more and more stressed as the demand for a secure, reliable and clean form of electrical energy is growing exponentially. The need to de-carbonize the grid triggers the deployment of some large-scale wind farms in today's power system [2]. Transmission System Operators (TSO) are busy trying to understand how these large-scale wind can harm their transmission grids during extreme operating conditions. In most electricity markets, Transmission System Operators operate their existing grids around the nose, the voltage stability limit, and there is a higher risk for the voltage to collapse. The problem is worsened when they are dealing with Renewable Energy resources such as wind energy which is difficult to forecast [3].

As such, the Transmission System Operators need to be equipped with sophisticated tools to determine when the power system is on the verge of entering into voltage instability mode so that systems planning can take control actions. During high wind penetration levels, they have to dispatch the wind power to the Load Serving Entities so that the customers can enjoy cleaner and cheaper electrical energy. Sometimes, it is not so easy since the congestion of the transmission lines impedes the evacuation of the wind energy. In addition, voltage stability margin might be another concern. At the same time, they are focused, during the operation of the power system, to maintain system security within an acceptable range. System security deals with the practices that are designed to keep the power in operation reliably if components fail [4]. Transmission Systems Operators make profits when they are injecting electrons into the grid. Consequently, they are uncomfortable dealing with the word TRIP all the time. They want to operate their grids in a way with a low probability of system blackout or equipment damage.

To assess the security of the power system [5]–[7], defined in Fig. 1, system monitoring and contingency analysis are used. The first one gives to the operator the up-to-date information about the current state of the power system to detect abnormal conditions in the power system and the latter one gives the list of the possible contingencies to be checked accompanied by their probability of occurrence [8]. In performing the contingency analysis, the operator is trying to come up with the list of contingencies that, if occurred, will harm the operating states of the system. Most of the time, contingencies are ranked after performing $N-1$ analysis [9]. In our present work, the stability of a wind-dominated power system is discussed based on Q-V and P-V methodologies and some $N-1$ contingencies with the Remedial Action Schemes (RAS). Furthermore, a methodology to rank the worst contingencies and to predict the voltage collapse during the highest wind penetration level is presented. Simulations have been extensively carried out to examine the methodology and have provided valuable information about the static security of the wind-dominated power system. The results can be used by the transmission system operator to anticipate voltage instability or voltage collapse in the power system during high

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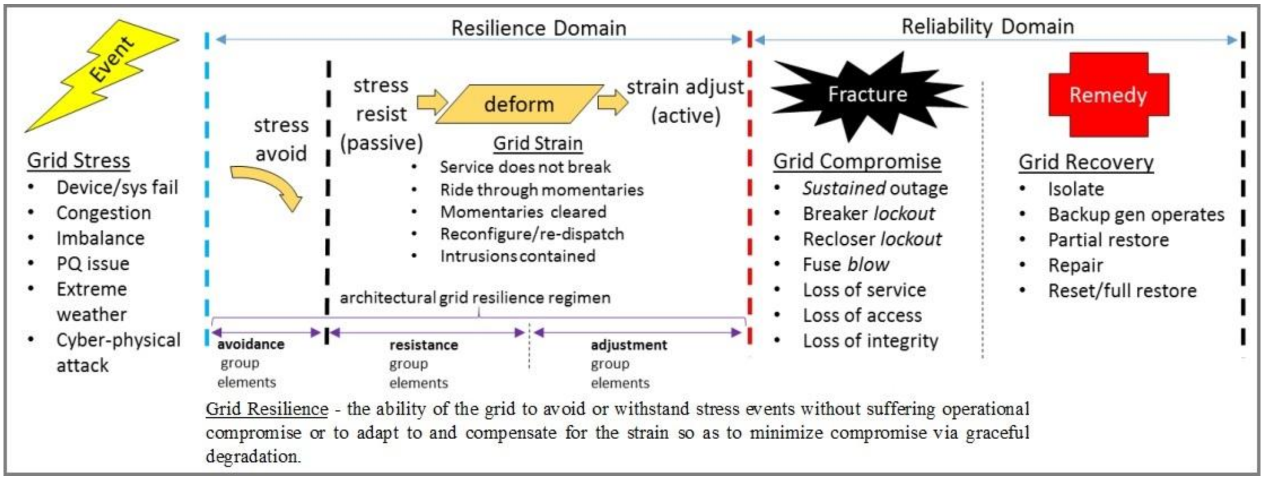

Fig. 1. Security of a Power System [5],[6].

wind penetration levels. Since it is impractical to test our methodology on a real power system, the IEEE-14 bus system is used for this purpose. This paper is a continuation of our previous work in [10]–[12].

II. Detection of the Weakest Bus

A. Voltage Stability Margin Computation

Voltage Stability Margin (VSM) is a measure of the difference between the loadability limit and the present operating load level or between the initial voltage operating point to the voltage critical point. As such, VSM can be obtained through formula or graphically under the PV or QV curve. VSM can be expressed as [13],

$$VSM = \frac{V_{initial} - V_{critical}}{V_{critical}} \tag{1}$$

where, $V_{initial}$ is the normal operating bus voltage and $V_{critical}$ is the voltage collapse point of the bus.

Additionally, using any PV or QV curve, the initial operating point and voltage critical point can be used to form a right angle triangle and the associated hypotenuse distance is the VSM as shown in Fig. 2. This relationship can be expressed in (2) and (3),

$$VSM(P) = \sqrt{(\Delta V_P)^2 + (\Delta P)^2} \tag{2}$$

$$VSM(Q) = \sqrt{(\Delta V_Q)^2 + (\Delta Q)^2} \tag{3}$$

where,

$$\Delta V_P = V_{P_{initial}} - V_{P_{critical}} \tag{4}$$

$$\Delta P = P_{initial} - P_{critical} \tag{5}$$

$$\Delta V_Q = V_{Q_{initial}} - V_{Q_{critical}} \tag{6}$$

$$\Delta Q = Q_{initial} - Q_{critical} \tag{7}$$

The relationship of (2) and (3) can be combined and modeled in PQV region corresponding to Reactive Power Margin.

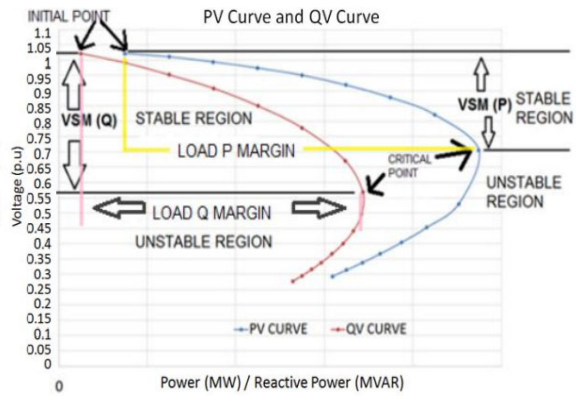

Fig. 2. Stability Regions on PV and QV Curves [14].

Hence, it can be said that the weakest bus of a system, determined from the VSM, can be subjected to the greatest amount of reactive power compensation. This relationship is shown in Fig. 3.

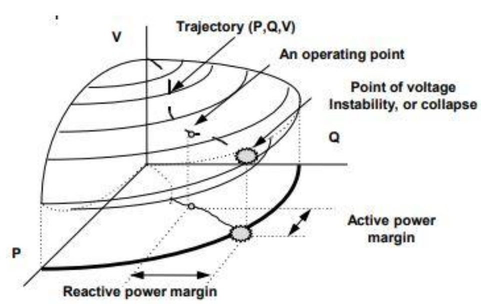

Fig. 3. Reactive Power Margin Determination [15].

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B. Determination of the Weakest Bus in the IEEE 14-Bus System

Previous literature suggest that graphical methods provide more reliable VSM than using (1) because the corresponding VSM is synchronized with the load buses and power flow [13], [14]. In this work, a power flow is first ran on the IEEE 14-Bus System shown in Fig. 7. To obtain either a PV or QV curve, the value of P load or Q load is increased by 0.1 p.u. for iterative values of load bus voltage. Hence, representing the various P or Q load to corresponding load bus voltage provides the PV or QV curve at a given bus. In this work, (3) is used on the QV curve and the resulting *VSM(Q)* is obtained as shown in Fig. 4. Hence, it is evident that the weakest bus is Bus 14 and the best observation of the DFIG impacting the system will be seen by integrating it at this bus. In the context of this work, wind penetration level is the ratio of the summation of the installed wind capacity and the total load.

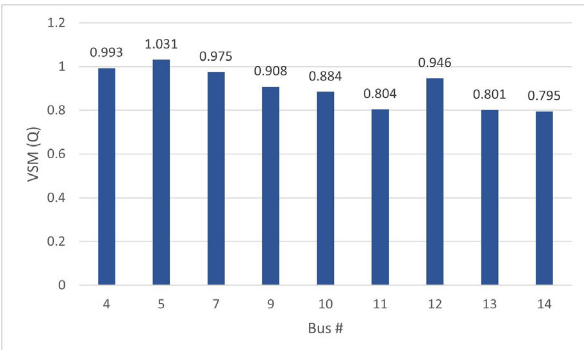

Fig. 4. VSM(Q) obtained by the hypotenuse distance under the respective QV curve.

$$Penetration\ Level = \frac{\Sigma Installed\ Wind\ Capacity}{\Sigma Load} \tag{8}$$

The transfer margin can be viewed as the ratio of the percentage increase in load (MW) and the base case power computed in the PV analysis.

$$Transfer\ Margin\ (TM) = \frac{MW_{PV} - MW_{base\ case}}{MW_{base\ case}} \tag{9}$$

III. Ensuring Reliability of the System Trough FACTS Devices

In the realm of transmission reliability, FACTS controllers are placed at various locations to recover the system from various voltage collapse due to stressed conditions via reactive power support [16], [21]. In this work, a shunt STATCOM is mainly used. An actual representation of a STATCOM unit connection into a grid is shown in Fig. 5.

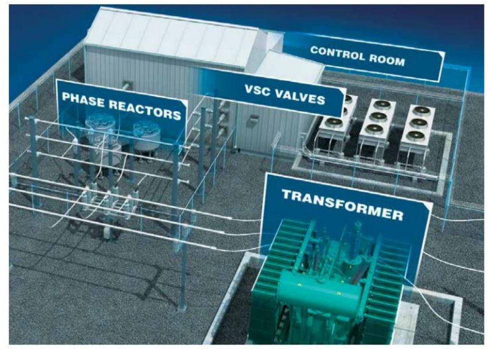

Fig. 5. A typical STATCOM unit connected in a power sytem [17].

The use of any FACTS devices depends on the health of the system and the specific issue that deems critical to alleviate. Depending on the issue, the specific FACTS device that, by configuration, contributes most to alleviating will be the most optimal solution. STATCOM was selected due to the voltage profile observed after the first part in Section V, shown in Fig. 8. The greatest concern was the drastic fluctuation in voltages especially to low voltage situations. An ideal feature of a shunt connected STATCOM is that it is able to either generate a capacitive or inductive output current regardless of the AC system voltage [17]. Hence, increasing system stability and power quality, in this work, through voltage control support, reactive power control, and increasing power transfer capacity due to it consisting of a Voltage Source Converter (VCS) connected to the grid by a step-up transformer and phase reactors. The Advanced Digital Control (ADC) system of the STATCOM, can take the input of the Voltage Transformer, and output a voltage higher in magnitude of the system. Thus, allowing the STATCOM to either operate in capacitive mode, produce a leading output current, generate reactive power and supply this reactive power to the grid or vice versa. In this work, the STATCOM is contributing in capacitive mode shown in Fig. 6.

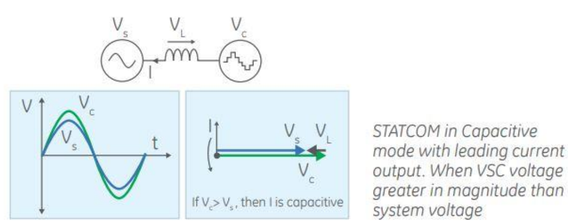

Fig. 6. Operation of STATCOM in Capacitive Mode [17].

Furthermore, optimal location of any FACTS devices leads to the most effective way of improving maximum loadability and voltage profile of the system. As such, we begin by addressing the objective function. There exists an optimal location for the STATCOM where maximum loadability is most secured especially under stress [18]. To obtain, both real and reactive power loads are increased in an exact loadability ratio or factor. Hence, the objective function is modeled as,

$$Max\ \lambda \tag{10}$$

where λ (in p.u.) is the loadability factor.

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The power balance equations can be expressed with the loadability factors as follows,

$$P_{gi} - \lambda P_{di} = P_i \tag{11}$$

$$Q_{gi} - \lambda Q_{di} = Q_i \tag{12}$$

for any given bus and where,
P_g: real power generation
P_d: real power demand
P_i: injected active power
Q_g: reactive power generation
Q_d: reactive power demand
Q_i: injected reactive power

and under the following constraints: (a) real power generation, (b) reactive power generation, (c) bus voltage and (d) transmission line. The aforementioned are represented respectively as follows,

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{13}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \tag{14}$$

$$|V_i^{min}| \leq |V_i| \leq |V_i^{max}| \tag{15}$$

$$|S_l| \leq |S_l^{max}| \tag{16}$$

IV. N-1 Contingency Analysis

A. Types of Violations

In the operation of their transmission grid, Transmission System place a great deal of emphasis to what they call the three Cs of transmission security. These three Cs are: Contingency, Constraint and Congestion. In the realm of power market operation, a contingency can be seen as any event that can jeopardize the reliability of the power system. As a result, security violation in the power system is always a Contingency/Constraint pair. The Transmission System Operators use their state estimator to perform a what they call a Real Time Contingency (RTCA) to generate a list of constraints. This action is done every 5 minutes.

The most common types of contingencies are line and generator contingencies [19]. These mostly cause two types of violations as follows:

- *Low Voltage Violations*: This is observed at buses. Thus, indicating the bus voltage is lower than a specific value. Typically, the operating bus voltage are in the ranges of 0.95 p.u. to 1.05 p.u. Anything, below 0.95 p.u., indicates the bus is experiencing a low voltage. Similarly, if the voltage rises above 1.05 p.u., then there is over-voltage at the bus. In power systems, the cause of voltage problems is commonly due to reactive power. Therefore, to fix problems of low voltage at a bus, reactive power is supplied to increase and improve the voltage profile. Similarly, to alleviate high voltage problems at a bus, reactive power is absorbed at the bus. Thus, maintaining a normal voltage of the system.
- *Line MVA Violations*: In transmission planning, it is imperative to consider the mediums used to interconnect various devices in the system. This type of violation exists when the MVA rating of a line exceeds its rating. The most commonly cause, is when the current flowing through the line exceeds the current capability. By industry standards and practices, the lines proposed are based on a safety margin of at least 25%. That is, the line should be able to withstand 125 % of the MVA limit. For safety, alarms are declared if the current crosses between 80 % to 90 % of the limit.

The Transmission System Operator has a list of corrective actions to take that my comprise curtailing or tripping of some generations, curtailing or tripping load or re-configuring the system. They do so to meet the NERC reliability standards which include to keep an acceptable system voltage, to keep an acceptable power flow and to limit the impact of cascading [22]. However, RAS are costly solutions to the transmission system, they have to avoid to use them frequently to keep the power system reliable. Sometimes, the decision to perform a new remedial action scheme or even a larger transmission grid upgrade is included in the interconnection studies process of the generator. In the complicated process, the focus is put on system reliability, deliverability and infrastructure cost while the expected energy cost is ignored.

V. Test System Modeling and Analysis

The IEEE 14-Bus System is used and modified for needs of this investigation. Upon determining the weakest bus of the system, it is implied that the most optimal reactive power compensation takes place here. As indicated in [10], the IEEE 14-Bus System comprises of 5 synchronous machines, where 3 are synchronous compensators and 2 generators. Furthermore, it comprises of 11 loads, 16 lines, 4 transformers, 5 PV or load buses (Buses 04, 05, 07, 09 and 14) and 1 shunt (Bus 08) shown in Fig. 7.

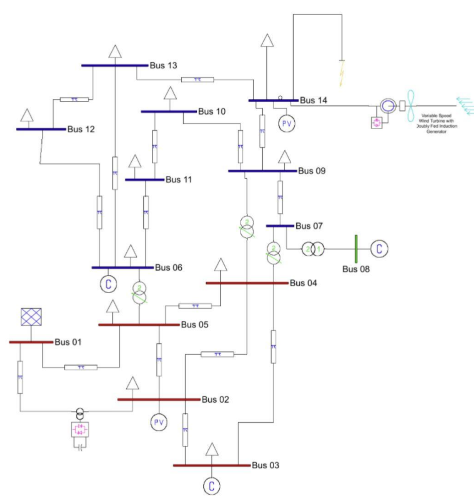

Fig. 7. One line diagram of the test system [10]–[12].

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TABLE I
VOLTAGE AT BUS 14 FOR N-1 CONTINGENCY WITH STATCOM AND WITHOUT STATCOM.

From bus	To bus	Outage line	V_{14} without STATCOM	V_{14} with STATCOM
1	2	Line 1	0.917	0.995
1	5	Line 2	0.932	1.001
2	3	Line 3	0.929	0.995
2	4	Line 4	0.927	0.999
3	4	Line 6	0.932	1.002
4	5	Line 7	0.933	1.001
4	7	Line 8	0.926	1.001
4	9	Line 9	0.922	1.004
5	6	Line 10	0.925	0.998
6	11	Line 11	0.934	1.001
6	12	Line 12	0.923	1.002
6	13	Line 13	0.908	0.997
7	8	Line 14	0.934	1.001
7	9	Line 15	0.900	0.998
9	10	Line 16	0.939	1.003
9	14	Line 17	0.887	1.007
10	11	Line 18	0.937	1.002
12	13	Line 19	0.933	1.003
13	14	Line 20	0.920	1.005

As already indicated in Section II, the weakest bus is Bus 14. Thus, the greatest amount of reactive compensation can be injected here. As such, the first modification is placing the wind farm here. The DFIG topology supplies reactive power compensation. During the $N-1$ condition, the line between busbar 2 and 4 is removed and the power flow is done. The reason behind this action is to check for congestion which is the situation where the transmission lines are incapable to accommodate all loads during peak demand or emergency demand like $N-1$ or $N-2$ or worse. It is worth reminding that grid congestion affects the reliability and efficiency of the transmission lines. Furthermore, it impacts the electricity market operations since retailers may not access the cheapest energy source. Following the Blackout 2003, the energy policy act 2005 established a mechanism to help ameliorate the efficiency, reliability, and capability of the grid. The Contingency Analysis has been done and all lines and the voltage at each bus are checked and the results show that the test system is $N-1$ secure. In the presence of $N-1$ contingency, the power system does not exhibit a healthy voltage profile, i.e. without the STATCOM as shown in Table I.

Similar to [10], [11], a STATCOM rated at 150 MVAR is placed at Bus 2 in Var control mode to imitate a capacitance, and regulate the injection of reactive power into the grid. Fig. 8 shows how the use of STATCOM significantly provides a healthy voltage profile upon a contingency analysis. The STATCOM was able to bring back the voltage at Bus 14 to an acceptable limit for both steady-state operation and during a contingency.

It is also imperative to determine the maximum power that can be integrated at Bus 14. Power flow analysis is performed at different wind penetration levels. This iterative process ensures the power system is secured at each level like that of [12]. In Table II, it shows that the power system approaches instability at anything above 600 MW and complete voltage collapse at 630 MW when integrated at Bus 14.

Since Bus 14 is the weakest bus of the system, the most severe contingencies are lines $9-14$ and $13-14$ outages. Consideration of all possible contingencies might be unrealistic and impractical to consider. The dispatcher needs to check for the reliability and the safe operation of the power system. They make periodic calculations to assess the reliability of the system. The power system ought to maintain safe and reliable operation throughout these contingencies. The stability limits of Bus 14 was computed using the steady state voltage stability analytical P-Q method and the impact of the contingencies on the stability margins of the bus are illustrated in the Table III and IV.

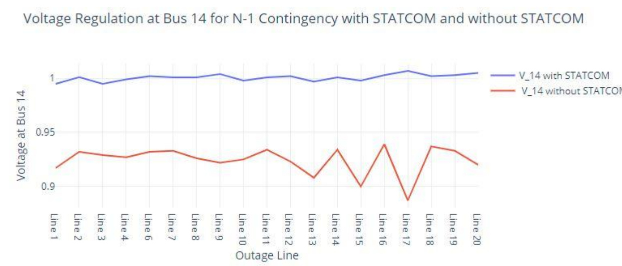

Fig. 8. Voltage Profile of Worst Contingency Assessment with and without STATCOM.

TABLE II
STABILITY LIMITS FOR MAXIMUM WIND INJECTION FROM BUS 14

Wind Penetration Level	Stability Margin
100 MW at 0.95 lagging	155.35 Mvar
200 MW at 0.95 lagging	163.64 Mvar
400 MW at 0.95 lagging	120.89 Mvar
600 MW at 0.95 lagging	22. 86 Mvar
630 MW at 0.95 lagging	Voltage collapse

TABLE III
STABILITY LIMITS FOR BUS 14 WITH LINE $6-13$ OUTAGE

Wind Penetration Level	Stability Margin
100 MW at 0.95 lagging	121.6 Mvar
200 MW at 0.95 lagging	93.57 Mvar
300 MW at 0.95 lagging	97.81 Mvar
400 MW at 0.95 lagging	30. 397 Mvar
600 MW at 0.95 lagging	Voltage collapse

TABLE IV
STABILITY LIMITS FOR BUS 14 WITH LINE $13-14$ OUTAGE

Wind Penetration Level	Stability Margin
100 MW at 0.95 lagging	85.98 Mvar
200 MW at 0.95 lagging	67.77 Mvar
300 MW at 0.95 lagging	21.57 Mvar
400 MW at 0.95 lagging	Voltage collapse

The results in Tables III and IV clearly show that the power system is on the verge of going into voltage collapse with the outages of lines $13-14$ and $9-14$. The wind power production might need to be curtailed to avoid the voltage collapse of the system.

VI. CONCLUSIONS

The traditional power system is under massive changes, and at the same time, it is being more and more stressed

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than before. With the integration of some large-scale wind farms into the transmission grids, keeping the power system in operation safely and reliably is more complicated. In the presence of high wind power penetration, the control of the power is a complex task for the Transmission System Operator. The voltage stability of the power is very fragile in the sense that if the strength of the power system is not assessed, the voltage of the system might collapse. Additionally, during the worst contingencies that might occur, the power system might not be able to survive. Hence, the Transmission System Planners and operators need to be equipped with valuable tools to plan, design and operate the power system economically under the constraint of keeping maximum reliability. Moreover, the operators need to some remedial actions to keep serving the load entities services. RAS are very costly to the grid operators and need to minimize their utilization. With the deployment of massive amount of renewable energy into the grid, remedial actions schemes can help to manage the transmission congestion.

This paper has attempted to present to the Transmission System Planners and Operators a methodology to assess the voltage stability of the transmission grid with high penetration of wind energy. Furthermore, the worst contingencies are considered to assess if the power system can deliver reliably the power to the Load Serving Entities inside its electricity market area. The $N-1$ contingency is considered since it is the most probable contingency in a power system. The results have demonstrated that during the $N-1$ contingency, the amount of wind power that can be integrated is much less than during the amount in steady operation. Based on the strength, the P-V and Q-V analysis, the maximum power transfer to the transmission grid has been determined. If more wind farm is injected, the power system will collapse and create a blackout. The Transmission System Operation might need to request to curtail the wind power production from the wind farm. The results can be used by the transmission system operator to anticipate voltage instability or voltage collapse in the power system during high wind penetration levels.

Acknowledgment

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