Distribution System Voltage Stability Analysis with Wind Farms Integration

Ce Zheng, *Student Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*—As the installed capacity of wind power generation is increasing continuously, its impacts on system voltage stability have been intensively studied in recent days. In this paper, only the wind farms connected to distribution network are treated. Wind gusts will produce output power spikes and cause poor feeder voltage regulation, which may lead to voltage collapse when there is no sufficient reactive power support. An accurate voltage stability index (VSI) is needed to quantify the voltage stability margin in real time. This paper addresses such an index for distribution systems, where the required measurements are available only at feeder roots. The proposed VSI has been implemented in simulations with wind farms integrated. Simulation results are presented to examine the performance of both fixed-speed wind turbine and variable speed wind turbine. STATCOM is also included to demonstrate its capability for voltage stability improvement.**

***Index Terms*—Voltage stability, wind turbine, reactive power, distribution system**

I. Introduction

Recently, wind farms continue to expand both in size and in capacity. It is expected in Texas that between 8% and 11% of the state electricity will come from wind resources by 2015. The Department of Energy (DOE) is exploring an energy scenario in which 20% of U.S. electricity is provided by wind by 2030 [1]-[2].

Wind farms connected to transmission grid and distribution network post a great challenge on the stability of an existing power system. Sudden wind gusts produce output power spikes and affect the stability of node voltages. If the node voltage stays too low, wind farms connected to that node may be tripped due to AC undervoltage protection. Further, without sufficient reactive power support, voltage instability may lead to voltage collapse [3]. Immediate warning of voltage instability is significant in maintaining normal operation of both wind farm and the whole system.

An intensive study of voltage stability indices started in 1990s. At that time, the system voltage stability was evaluated using very limited measurements [4]. Later, with the development of data acquisition technique, especially the time synchronized measurements between different locations, detection of the onset of voltage stability became more accurate [5]-[8]. A sensitivity-based approach to compute voltage stability along the system trajectory using Phasor Measurement Unit (PMU) measurements was proposed [5]-[6]. The method proposed in [7]-[8] calculates the voltage stability margin by computing the Maximum Loadability Index (MLI) using data from PMUs.

Today, the importance of voltage stability analysis has been reemphasized because of the large integration of renewable resources, especially the wind power. A few studies that explore the interaction between wind farms and the node voltage stability have been reported [9]-[13]. Most of the papers are concentrated on the voltage stability of transmission systems.

Traditionally the wind farms utilize fixed-speed wind turbines, mostly the Squirrel Cage Induction Generator (SCIG), to produce power. The SCIG-based wind farms don't serve the function of voltage regulation and absorb reactive power from the utility grid. Now, variable speed wind turbines have become more common than traditional fixed-speed wind turbines. They had about 60% market share around the world in 2004 [14]. The variable speed wind turbines are either Doubly Fed Induction Generators (DFIG) or full power converters. A built-in AC-DC-AC voltage source converter isolates the wind turbine from the outside system and functions like a STATCOM to provide required reactive power. The use of variable speed wind turbines usually has no negative impacts on the node voltage, and they even have the capability to enhance the voltage stability [15]-[18].

This paper investigates the impacts of different types of wind turbines on the distribution system voltage stability. We have proposed a simple and accurate voltage stability index (VSI) which, after modification, could adapt to the situation of distribution system, where the measurements are available only at feeder root. The local measurements are used to compute the VSI in real time. The method accommodates the time skew of SCADA data. No time synchronization or information exchange between the monitoring locations is needed for the index calculation. Using the voltage stability index, the paper has examined the performance of both fixed-speed and variable speed wind turbines in a distribution network. The effectiveness of the index is also demonstrated by simulation results.

The paper starts with a theoretical formulation of the proposed voltage stability index (VSI). After that the VSI is modified to adapt to the situation of distribution system voltage stability analysis. A test system to examine the impacts of wind turbines on node voltage stability is established then. Simulations are implemented and simulation

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results are analyzed at the end.

II. Voltage Stability Index

The proposed voltage stability index will be formulated in this section. Consider a transmission line within a power system of any number of buses. The line equivalent model is represented in Fig. 1.

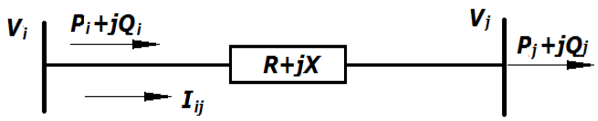


Fig. 1. Equivalent model of a two-bus transmission system

Assume Bus i is the sending end and Bus j is the receiving end. The sending end voltage could be computed as below

$$\begin{aligned} V_i &= V_j + I \cdot (R + jX) \\ &= V_j + \frac{S_j^*}{V_j^*} \cdot (R + jX) \\ &= V_j + \frac{P_j - jQ_j}{V_j^*} \cdot (R + jX) \\ &= \frac{|V_j|^2 + P_j R + Q_j X + j(P_j X - Q_j R)}{V_j^*} \end{aligned} \quad (1)$$

Substitute the voltage by its magnitude, (1) is rewritten as

$$|V_i| = \frac{\sqrt{(|V_j|^2 + P_j R + Q_j X)^2 + (P_j X - Q_j R)^2}}{|V_j|} \quad (2)$$

Rearrange (2) and the following is obtained

$$|V_j|^4 + [2(P_j R + Q_j X) - |V_i|^2] \cdot |V_j|^2 + (P_j R + Q_j X)^2 + (P_j X - Q_j R)^2 = 0 \quad (3)$$

To guarantee that (3) is solvable, the following inequality constraint should be satisfied

$$|V_i|^4 - 4|V_i|^2(P_j R + Q_j X) - 4(P_j X - Q_j R)^2 \geq 0 \quad (4)$$

With the increase of the receiving end power demand $P_j + jQ_j$, the left side of (4) approaches zero, and the two-bus network reaches its maximum power transfer limit. From the steady-state/long-term voltage stability point of view, the maximum power transfer limit represents the "nose point" of the PV curve, at which the node voltage becomes unstable. Thus a voltage stability index could be extracted from (4).

To simplify the problem, a constant power factor at Bus j is assumed. $P_j + jQ_j$ could be then substituted by $(P_j + jQ_j) \cdot VSI$. VSI is the proposed voltage stability index having the following characteristics:

- VSI is greater than 1 when the transmission line is within its power transfer limit;
- VSI is equal to 1 when the transmission line is reaching maximum power transfer capability;
- When VSI is less than 1, maximum power transfer limit is violated, and voltage becomes unstable.

Replacing $P_j + jQ_j$ by $(P_j + jQ_j) \cdot VSI$ in (4), we get

$$|V_i|^4 - 4|V_i|^2(P_j R + Q_j X) \times VSI - 4[(P_j X - Q_j R) \times VSI]^2 \geq 0 \quad (5)$$

By making the left side of (5) equal to zero, and extracting VSI, one is obtaining the voltage stability index for a general two-bus system.

The focus of this paper is to analyze the distribution system voltage stability with wind farms integrated. To accomplish this, the network shown in Fig. 1 has been considered as a distribution feeder, of which Bus i is the feeder root and Bus j is load bus. Further, modification of the VSI in (5) is needed to adapt to the situation of distribution system.

Since in distribution system the monitoring devices are usually installed at the feeder root (substation), we need to replace the receiving end power quantities in (5) using the sending end measurements. In Fig. 1, Bus j powers could be replaced by Bus i powers using (6)

$$P_j + jQ_j = P_i + jQ_i - (R + jX)|I|^2 \quad (6)$$

Integrating (5) and (6), one gets

$$VSI = \pm \frac{\sqrt{[4|V_i|^2(P_j R + Q_j X)]^2 + 16|V_i|^4(P_j X - Q_j R)^2}}{8(P_j X - Q_j R)^2} - \frac{4|V_i|^2(P_j R + Q_j X)}{8(P_j X - Q_j R)^2}$$

(Because the value of VSI is always greater or equal to zero, here we neglect the negative solution)

$$VSI = \frac{\sqrt{\begin{array}{c}[4|V_i|^2((P_i - |I|^2 R)R + (Q_i - |I|^2 X)X)]^2 + \\ 16|V_i|^4((P_i - |I|^2 R)X - (Q_i - |I|^2 X)R)^2\end{array}}}{8((P_i - |I|^2 R)X - (Q_i - |I|^2 X)R)^2} - \frac{4|V_i|^2((P_i - |I|^2 R)R + (Q_i - |I|^2 X)X)}{8(P_j X - Q_j R)^2} \quad (7)$$

After rearranging (7), the proposed voltage stability index for distribution system is obtained as below

$$VSI = \frac{|V_i|^2\sqrt{[(P_i - |I|^2 R)^2 + (Q_i - |I|^2 X)^2](R^2 + X^2)}}{2(P_i X - Q_i R)^2} - \frac{|V_i|^2[(P_i - |I|^2 R)R + (Q_i - |I|^2 X)X]}{2(P_i X - Q_i R)^2} \quad (8)$$

III. Test System with Wind Farm

Fig. 2 shows the single line diagram of a test distribution system. The switchable load at Bus 3 is fed by two power sources: one is the transmission system through a distribution feeder; the other is a local wind farm.

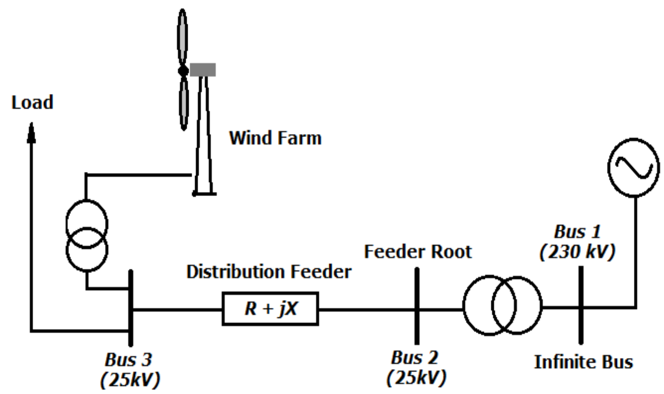


Fig. 2. Single line diagram of the test system with wind farm integration

The feeder root is connected to the transmission system through a transformer connected at Bus 1. The outside transmission system is considered as a power source (infinite bus) with a constant voltage of 230 kV. The voltage level of Bus 2 and Bus 3 is 25 kV. The feeder has a length of 25 km with an impedance of $2.88 + j9.896\ \Omega$.

The wind farm is connected to Bus 3 through a step-up transformer. To evaluate the impact of wind farm on local voltage stability, the cases of using two types of wind turbines will be used to perform the analysis: one is the conventional SCIG wind turbines and the other is DFIG wind turbines.

For the first case (turbine type), the wind farm contains three pairs of SCIG wind generators (WG). They are WG#1, WG#2 and WG#3. Each of the six turbines has a rated real power generation capacity of 1.5 MW. The wind farm has a rated total capacity of 9 MW. Besides the capacitor banks already integrated inside the wind farm, a switchable STATCOM is connected to the Point of Common Coupling (PCC) at Bus 3 for additional reactive power needs. The test scheme for this type of wind farm is shown in Fig. 3.

For the second type, the wind farm is arranged the same as in Fig. 3 except that the capacitor banks and STATCOM are removed. This is because the DFIG is able to control the terminal voltage through its electronic-based AC/DC voltage source converter, and no additional reactive power compensation devices are needed.

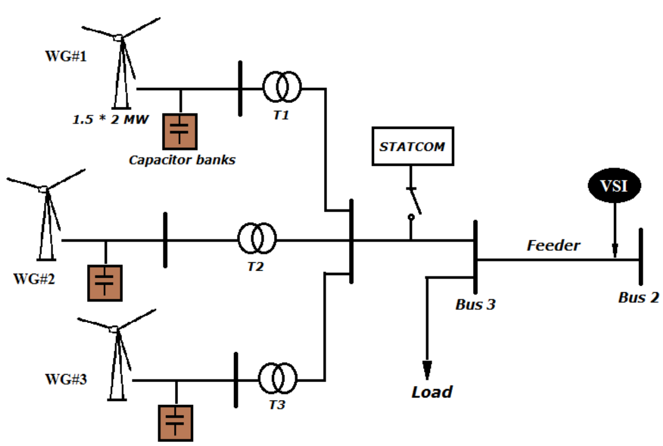


Fig. 3. Details of the SCIG-based wind farm and reactive power compensators

For both types of wind farm, the VSI is computed using local measurements at feeder root (Bus 2) in order to monitor the voltage stability of Bus 3.

Further, when configuring the test system, the control scheme of "Voltage Regulation" of the DFIG wind turbines is selected to maintain the terminal voltage level at Bus 3.

IV. Simulation

In our work, the Matlab/Simulink is used to establish the test system shown in Fig. 2 and Fig. 3.

A. Modeling of VSI

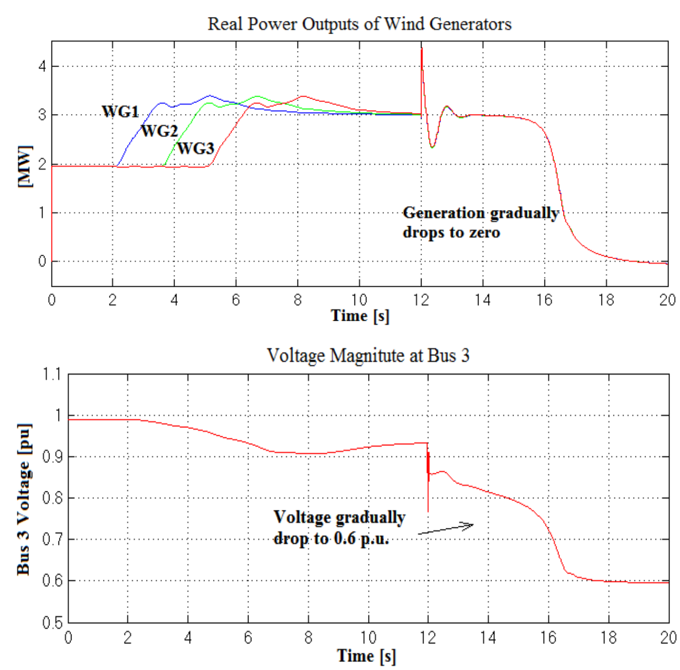
The proposed voltage stability index is modeled in Matlab and shown in Fig. 4. The real-time calculation of the index could be divided into three consecutive steps.

Firstly, the real-time bus measurements, as well as the feeder resistance and inductance are imported as inputs for the model to use. In this case, the required bus measurements include the voltage, current, as well as real and reactive power at Bus 2. Secondly, the data measurements are processed according to (8). The final procedure is to output the real-time value of the voltage stability index.

B. Case Study: SCIG-based Wind Farm without STATCOM

This case will study the impact of SCIG-based wind farm on voltage stability. A wind gust is assumed to occur at t=2s. The wind speed at WG#1 increases from 8m/s to 11/s within 3 seconds. The same wind gust is applied to WG#2 and WG#3, respectively with 1.5 seconds and 3 seconds delays.

STATCOM are switched out first. Also disabled is the AC undervoltage protection. Simulation is implemented with the load switching in at t=12s, with a constant power demand of 20+j10 kVA. Simulation results are shown in Fig. 5.



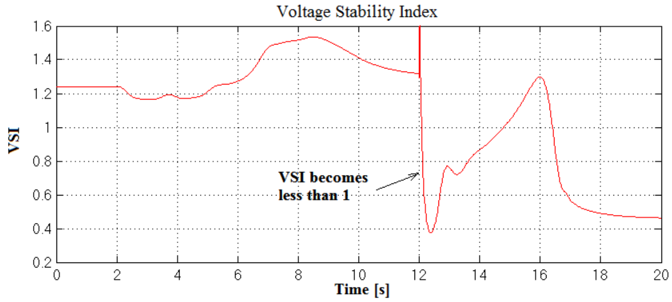


Fig. 5. Simulation results of SCIG-based wind farm with the AC undervoltage with protection disabled

As is shown in Fig. 5, the VSI becomes smaller than 1 soon after the load is switched in, which indicates that the voltage at Bus 3 is unstable. This could be verified by checking the voltage measurement at Bus 3. The Bus 3 voltage magnitude has dropped to 0.6 p.u. within 8 seconds. This case demonstrates that the VSI could effectively detect the onset of voltage instability.

Another simulation is implemented by enabling the AC undervoltage protection scheme for wind turbines. Simulation results are shown in Fig. 6.

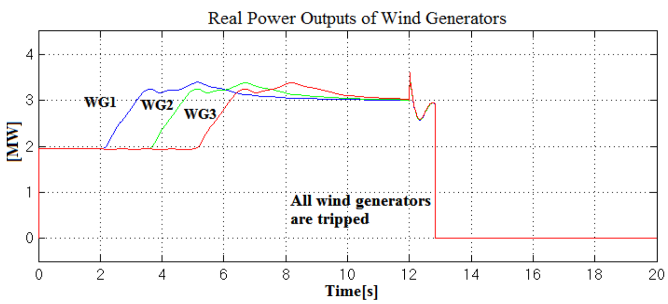


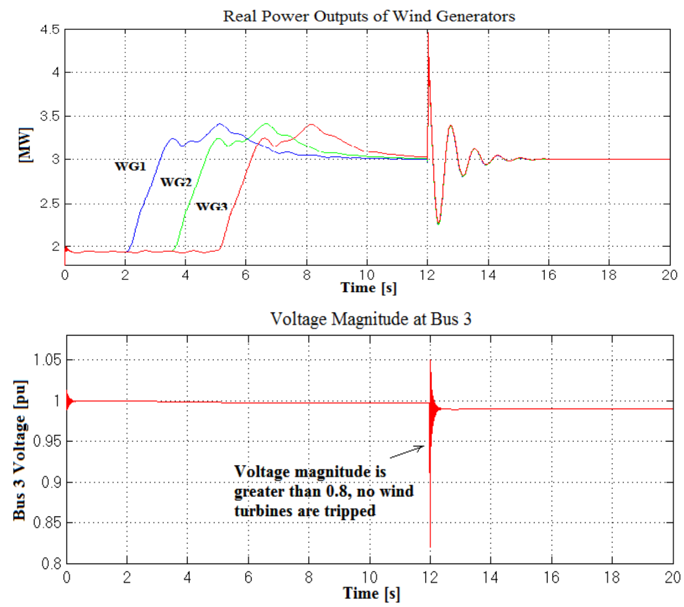
Fig. 6. Simulation results of SCIG-based wind farm with the AC undervoltage protection enabled

As shown in Fig. 6, about 0.9 seconds after the load is switched in, all of the wind generators have been tripped due to undervoltage protection. If one looks at the Bus 3 voltage, one can find that the voltage magnitude has dropped to as low as 0.76 p.u. before the wind generators are tripped.

The main reason for the voltage drops in the two simulations shown above is that the SCIG-based wind farm absorbs reactive power from the utility grid while generating real power, which makes the wind farm a reactive power "sink".

C. *Case Study: SCIG-based Wind Farm with STATCOM*

In this case, a STATCOM is combined at the PCC (Bus 3) to provide reactive power support. The converter rating of the STATCOM is set to be 30 MVA. The same load is switched in at t=12s. Fig. 7 shows the simulation results.



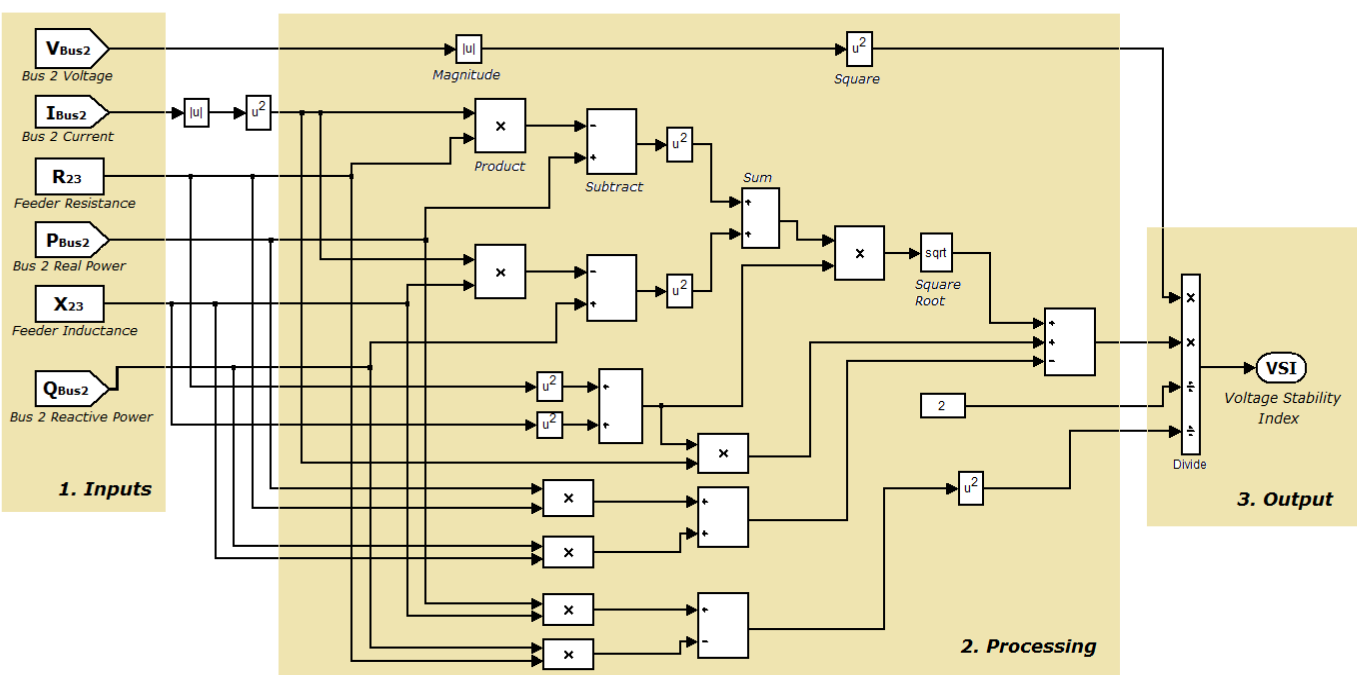


Fig. 4. Voltage Stability Index implemented in Matlab/Simulink

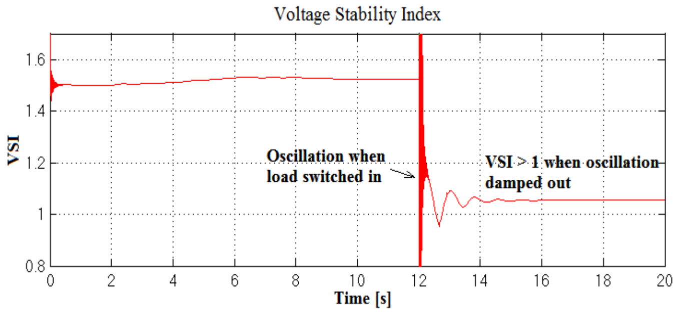


Fig. 7. Simulation results of SCIG-based wind farm with load and STATCOM

As it can be observed from Fig. 7, although some oscillations of the power outputs occur, all of the wind turbines remain in service after the sudden load increase. This is because the STATCOM has provided sufficient reactive power to support the node voltage at Bus 3.

D. Case Study: DFIG-based Wind Farm

This case looks at the impact of DFIG-based variable speed wind turbines on voltage stability. The gust of wind occurs at t=3s and increases the wind speed from 8m/s to 14m/s in six seconds.

Since wind turbines using DFIG are equipped with built-in PWM-based voltage source converter (VSC), the STATCOM is no longer needed and is removed from the test system. By switching in the same load at t=12s, simulation results are presented in Fig. 8.

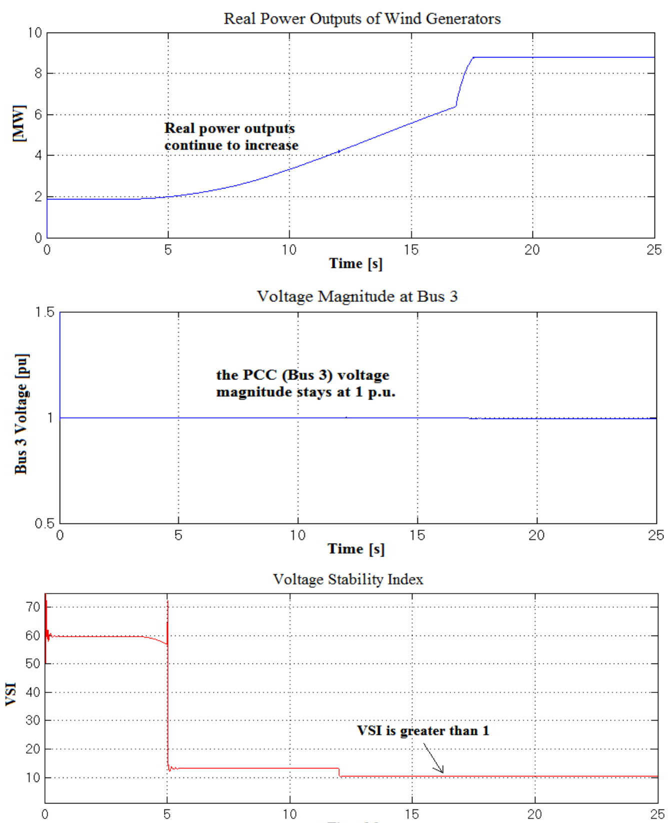


Fig. 8. Simulation results of DFIG-based wind farm with load and without additional reactive power compensation

Comparing Fig. 8 with Fig. 5, it could be found that the built in VSC could dynamically regulate its grid side voltage and maintain normal operation of the wind generators. Thus it performs better than the conventional SCIG-based wind turbines during gust of wind and sudden load increase.

V. Conclusions

This paper investigates the distribution system voltage stability with wind farms connected. The accomplishments reported in this paper include:

- A voltage stability index (VSI) to quantify the voltage stability margin for a general two bus system using time-synchronized data of the line two ends is proposed;
- The VSI is modified to adapt to the situation of radial distribution system. Only local measurements are used after the modification. No time synchronization is needed;
- VSI is tested using an artificial distribution system configuration with wind farms integrated;
- The performance of both fixed-speed and variable speed wind turbine are examined in simulations. Load switching and wind gusts are considered in studying the corresponding node voltage responses;
- STATCOM is also included to demonstrate its capability for voltage stability improvement;
- Simulation results demonstrate that the fixed-speed wind turbine requires large amount of reactive power support, whereas the variable speed wind turbine could enhance node voltage stability without additional reactive power compensation devices;
- The proposed VSI is shown to have the capability of effectively quantifying node voltage stability margin in real time.

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VII. BIOGRAPHIES

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