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# Varying Penetration Ratios of Wind Turbine Technologies for Voltage and Frequency Stability

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**Abstract**—This paper examines the ability of a power system to accommodate wind generation with varying ratios of doubly-fed induction generator and fixed speed induction generator turbines from both static and dynamic aspects. By controlling the ratio between the two types of turbines, voltage stability is maintained for steady-state conditions for a large range of varying wind speeds. Using the ratio determined from the static analysis, the dynamic analysis explores the voltage and frequency characteristics of the system under contingency conditions. An initial analysis was carried out on the IEEE 30 bus test system. The results of this analysis are presented in this paper and detail how by varying the ratio of the turbine types the frequency stability and voltage stability can be improved.

**Index Terms**—Wind Power Generation, Frequency Control, Power System Dynamic Stability

## I. INTRODUCTION

AS the trend towards renewable energy grows, wind energy is becoming the major source of renewable energy in today's power systems. These installations are predominately comprised of wind turbines that use the doubly-fed induction generator (DFIG). The DFIG effectively decouples the rotor of the turbine blades from the rotor of the electric generator through the use of a power electronics converter. This converter allows for the control of active and reactive power using constant power factor or constant voltage. Although this scheme provides voltage support for the farm, it has the significant disadvantage of not being able to utilize the inertia of the blades, thus limiting the ability of the DFIG to provide active frequency support in a power system during a loss of generation event. It has been shown that through the use of a supplementary controller, inertia can be emulated from the DFIG wind turbine [1]–[3]; however, this control must be implemented outside of the manufacturer's specifications.

The other commonly used wind turbine is the fixed speed generator (FSG). In the FSG, the rotor of the turbine blades is coupled to the rotor of the electric machine through a gearbox. This design allows the turbine to utilize the kinetic energy stored in the turbine blade, and contribute to system frequency stability by providing a level of spinning inertia. The disadvantage of the FSG arises in the fact that the machine is not capable of reactive power control, but rather absorbs large

levels of reactive power during normal operation. The reactive consumption of the FSG is generally offset using capacitor banks to achieve a constant power factor. However, capacitor banks are slow acting and do not prove effective during low voltage events and as a result, FSG farms often trip out of service. This is often referred to as the fault-ride through capability of the FSG [4], [5], and is of particular importance when installing FSGs into a power system. By using DFIG and FSG wind turbines together, the goal is to develop a ratio where the two turbine types complement each other, by contributing to the limitations of the other; DFIGs can provide the necessary voltage support and FSGs can provide frequency support to maintain system stability.

This study first aimed to determine if there was an appropriate ratio of DFIG wind turbines to FSG wind turbines to maintain voltage stability during normal and single line contingency events through steady-state analysis. Then, based on this ratio, could the dynamic voltage and frequency stability of the system be maintained? The steady-state and dynamic analyses will provide a ratio that is stable across the system. To refine that ratio the PV transfer capability from one area to another was implemented. This allowed for the identification of particular regions that needed more voltage support when compared to others in the system.

This study was carried out on the IEEE 30 bus test system, for both a static and dynamic analysis. These simulations were carried out in the PSS/E software platform, provided by PTI Siemens Inc. Through these analyses, this paper demonstrates how by identifying the initial ratio from the static voltage analysis, the wind turbine ratio can be further refined through frequency and dynamic voltage studies.

Section II of this paper covers the concepts and equations necessary for modeling the DFIG and FSG wind turbines in computer simulations. It details the equations governing the electrical and mechanical systems of the wind turbine types. Section III provides an overview of the methodology used to approach the stability problems. It details the steps taken to complete the steady-state and dynamic analyses associated with this study. Section IV reports the results of the voltage and frequency stability simulations. Section V, introduces the concept of using PV incremental transfer capability as means of assessing a particular areas need for voltage control, allowing a local refinement of the wind turbine ratio. Using the results of the simulations, it draws conclusions as to the effects of varying the wind turbine ratio in farms across the system. Section VI explores avenues for future work and Section VII is the conclusion of the paper.

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## II. WIND TURBINE MODELLING

### A. The Fixed Speed Induction Generator

Fixed speed generator (FSG) or squirrel cage induction generator wind turbines were the first generation of wind turbines to be installed widely in power systems around the world. The turbine is a short-circuit rotor induction machine, and the modelling concepts behind the machine are well established [6]. In the  $d$ - $q$  reference frame the stator voltage equations are given as follows:

$$\begin{aligned} v_{ds} &= R_s i_{ds} - \omega_s [(L_{s\sigma} + L_m) i_{qs} + L_m i_{qr}] \\ v_{qs} &= -R_s i_{qs} + \omega_s [(L_{s\sigma} + L_m) i_{ds} + L_m i_{dr}] \end{aligned} \quad (1)$$

The rotor is short-circuited so the rotor voltages sum to zero.

$$\begin{aligned} v_{dr} &= -R_r i_{dr} - s\omega_s [(L_{r\sigma} + L_m) i_{qr} + L_m i_{qs}] + \frac{d\psi_{dr}}{dt} \\ &= 0 \\ v_{qr} &= -R_r i_{qr} + s\omega_s [(L_{r\sigma} + L_m) i_{dr} + L_m i_{ds}] + \frac{d\psi_{qr}}{dt} \\ &= 0 \end{aligned} \quad (2)$$

The slip of the machine is defined as follows:

$$s = 1 - \frac{p}{2} \frac{\omega_m}{\omega_s} \quad (3)$$

The torque of the machine is given as:

$$T_e = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \quad (4)$$

The equation of motion for the generator is:

$$\frac{d\omega_m}{dt} = \frac{1}{2H_m} (T_m - T_e) \quad (5)$$

Finally, the equations used to represent the active and reactive power out of the machine are

$$\begin{aligned} P_s &= u_{ds} i_{ds} + u_{qs} i_{qs} \\ Q_s &= u_{qs} i_{ds} - u_{ds} i_{qs} \end{aligned} \quad (6)$$

(1) - (6) are used to represent the FSG in stability studies. The design of the FSG, require that large levels of reactive compensation be present, as the generator consumes large levels of reactive power. This is usually achieved in the form of shunt capacitance, to provide a fixed power factor at the FSG buses.

### B. The Doubly-Fed Induction Generator

The modelling of the DFIG is based on the same equations as those of the FSG however, the rotor current is no longer short-circuited. As a result, the equations representing the DFIG are as given in (7) - (9). The stator voltages are as follows:

$$\begin{aligned} u_{ds} &= -R_s i_{ds} + \omega_s [(L_{s\sigma} + L_m) i_{qs} + L_m i_{qr}] \\ u_{qs} &= -R_s i_{qs} - \omega_s [(L_{s\sigma} + L_m) i_{ds} + L_m i_{dr}] \end{aligned} \quad (7)$$

While the rotor voltages are given as:

$$\begin{aligned} u_{dr} &= -R_r i_{dr} + s\omega_s [(L_{r\sigma} + L_m) i_{qr} + L_m i_{qs}] \\ u_{qr} &= -R_r i_{qr} - s\omega_s [(L_{r\sigma} + L_m) i_{dr} + L_m i_{ds}] \end{aligned} \quad (8)$$

This results in the following power quantities:

$$\begin{aligned} P &= P_s + P_r = u_{ds} i_{ds} + u_{qs} i_{qs} + u_{dr} i_{dr} + u_{qr} i_{qr} \\ Q &= Q_s + Q_r = u_{qs} i_{ds} - u_{ds} i_{qs} + u_{qr} i_{dr} - u_{dr} i_{qr} \end{aligned} \quad (9)$$

The design of the DFIG allows for the production of reactive power, and through the implementation of a converter, the reactive power can be utilized to provide terminal voltage control [7]–[9]. The concepts behind this control are well established, and as a result will not be discussed in detail in this paper. Rather, it will focus on the utilization of this control to maintain voltage stability at the wind farm collector bus, using the DFIG, for both static and dynamic simulations.

### C. Inertial Constant of the FSG

The mechanical design of the FSG allows for a natural inertial response to a loss of generation event. The FSG acts in a similar manner to a synchronous generator and attempts to provide inertial response by utilizing the stored kinetic energy in the blades of the turbine. The level of inertia present in the blades combined with the inertia in the shaft will determine how quickly the FSG will respond to the event using equation (5). To determine this level, the inertial mass of the blades is calculated as follows. The inertia of any given body is:

$$J = \sum m_i r_i^2 \quad (10)$$

In (10),  $m_i$  is the mass of object  $i$  and  $r_i$  is the radius from the center of the object. For the blades of a wind turbine this yields:

$$J = 3m_b \left( \frac{r}{3} \right)^2 = \frac{1}{9} m_r r^2 \quad (11)$$

Here,  $m_b$  represents the mass of each blade and  $m_r$  is the cumulative sum of the blade and rotor structure, equivalent to  $3m_b$ . This value of inertia,  $J$  is converted to the inertial constant,  $H$  as follows:

$$H = \frac{J\omega_m^2}{2S} \quad (12)$$

This value of inertia is coupled through the shaft of the turbine and is represented at the generator side of the turbine as a single inertia. This representation is referred to as a lumped or single mass model. Although it has proven to be less accurate for short-term voltage stability simulations [10], based on the requirements of the software and limited availability of valid models, it was decided that a lumped mass model coupled to an induction machine would be used to represent the FSG for this initial study.

### D. Inertial Constant of the DFIG

As previously mentioned, the DFIG is unique in that the blades of the turbine are decoupled from the rotor of the electric machine. This means the inertia of the blades is not seen by the system, and the machine cannot respond to loss of generation events. There have been several studies that detail how the inertia of the blades can be utilized through the addition of a control loop [1]–[3], however this frequency

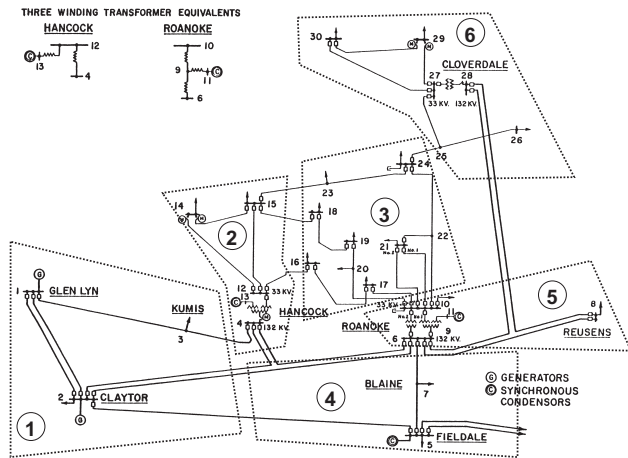


Fig. 1. IEEE 30 Bus Test System. The system has been split into 6 areas, wind generation connected at buses 5, 8, 14, and 18.

control ability is not present on standard DFIG turbines today. As a result during the dynamic simulations in this study, the power output of the DFIG was maintained at a constant level, to mimic the real-life response of the machine.

### III. METHODOLOGY

The purpose of this study was to determine the appropriate ratio that would maintain both frequency and voltage stability in a system with a significant level of wind power penetration. This section develops a process for analyzing the steady-state voltage stability for varying wind speeds, the frequency of the system for a loss of generation event, and the dynamic voltage during a faulting event.

#### A. Steady State Voltage Analysis

The goal behind the steady-state analysis was to determine how the voltage changed with varying ratios of DFIGs and FSGs connected at each farm in the system. To examine this effect, the generation and load in the IEEE 30 bus test system were modified appropriately to achieve a realistic wind penetration level. The structure of the system remained the same, generation and load were scaled up to allow for a larger penetration of wind generation in the system. The one-line diagram of the system can be seen in Fig. 1. Using PSS/E Power Flow and PSS/EWind, the system was modelled with a wind penetration level of 15.6% of the total system generation of 1478.29 MW, approximately 230.6 MW of wind generation. The system was divided into six operating areas. A single farm was placed in areas 2, 3, 4, and 5, while areas 1 and 6 operated using only normal conventional generation. This was done to mimic a real system where wind generation will be spatially distributed across the network. The generation at each wind farm was kept constant through all the simulations; only the ratio of DFIGs to FSGs within each individual farm varied from trial to trial. The rest of the generation in the system was provided by 5 conventional units. The wind farms and conventional units supplied the system load of 1270 MW and 295.24 MVars.

Beginning from a 50:50 ratio of DFIGs to FSGs, 500 iterative power flows were run while all of the bus voltages in the system were monitored. Each iteration consisted of a new set of random wind speeds being read into the wind turbine models, creating a new power output from the wind farms. This captured the variability of the wind and tested the ability of the power system to handle the large swings in power output from wind farms due to changing weather conditions. DFIGs and FSGs were connected to the system as separate farms that shared a common collector bus. The FSGs were compensated with capacitor banks to create a power factor of .95 inductive as is standard practice. Then, using the DFIG's reactive power control capability, the voltage was controlled at the collector bus. Following this analysis, the ratio of the turbines was changed and another set of iterative power flows was run. This process was completed several times and the results are reported in Section IV.

#### B. Dynamic Frequency Stability Analysis

Using the same power flow case from the static analysis, dynamic data was compiled for the conventional generating machines in the system [6]. Next, using PSS/EWind, wind generation was added to the system in the same manner as in the steady-state simulation. Beginning from the 50:50 ratio, wind generation was added to the system and the frequency of the system was monitored. It should be noted that wind generation was only added beginning at the 50:50 ratio due to the results of the steady state voltage analysis. This decision will be discussed later in Section IV.

The DFIG was modelled using the WT3 generic wind model provided by PSS/E [11]. The turbine consists of six components and models; the machine, the generator controls (including the WindVar control, available on the General Electric (GE) wind turbines), the turbine, the pitch control, and the voltage and frequency protection relays. A lumped mass model was used to represent the FSG. Using the a standard induction machine model, an inertial constant,  $H$ , of 3.45s was applied at the rotor. This value of  $H$  is consistent with the calculated  $H$  of standard FSGs [12]

#### C. Dynamic Voltage Stability Analysis

Working from the results of the previous two studies, a series of dynamic simulations were conducted to determine the voltage stability of the system under varying ratios of wind turbines. This study consisted of a set of fault simulations for the same turbine ratios from the previous studies. The fault was applied and the critical clearing time for the varying ratios was observed. Also, along with the critical clearing times, the system's ability to recover to its original voltage level was monitored at the most crucial buses. In this study, this would be at the buses where the FSGs were interconnected. This is due to the fault-ride through criteria of FSGs creating an increase in the FSGs sensitivity to voltage changes.

## IV. SIMULATION RESULTS

#### A. Steady-State Voltage Analysis

From the steady-state analysis, it was observed that there were significant changes in the voltage levels across the

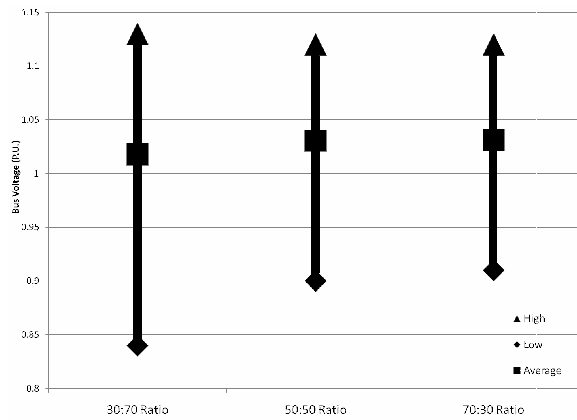


Fig. 2. Average bus voltage for each ratio (DFIG:FSG) as well as the maximum and minimum voltages seen for all iterations of the power flow.

buses in the test system as the ratio of DFIGs to FSGs changed. Beginning with the 50:50 ratio, simulations were run varying the penetration ratio from to 30:70 to 100:0. During these simulations, two ratios provided particularly interesting results. During the 30:70 ratio simulation, it was observed that voltages in the system were falling below desired operating levels in the system, reaching a minimum of 0.84 p.u.. The 70:30 ratio simulation was interesting in that it showed very little variation compared to the 50:50 ratio. The minimum voltage during the 70:30 ratio was 0.91 p.u., while it was 0.90 p.u. during the 50:50 ratio simulation. This would suggest that the 30:70 and 70:30 ratio represent the extremes of the DFIG penetration capability in the system.

Fig 2. shows the range of voltages associated with each ratio and summarizes the steady-state analysis. The 30:70 ratio had an average bus voltage of 1.0175 p.u., the 50:50 ratio had an average of 1.0306 p.u., and the 70:30 ratio had an average of 1.0313 p.u. This compared to the base case average, where there is no wind generation present in the system of 1.0293 p.u. As seen in Fig. 2, the voltage levels between the 50:50 ratio and 70:30 ratio are very similar. This implies that increasing the ratio beyond 70:30 of DFIGs to FSGs would not have a significant effect on the system's steady-state voltage stability. Table I summarizes the results of the steady-state voltage analysis. Based on these results the 50:50 ratio was used as the initial value for the dynamic simulations.

TABLE I  
VOLTAGE DISTRIBUTION FOR VARYING PENETRATION RATIOS

Ratio (DFIG:FSG)	30:70	50:50	70:30
$V_{max}$ (p.u.)	1.13	1.12	1.12
$V_{ave}$ (p.u.)	1.0175	1.0306	1.0313
$V_{min}$ (p.u.)	0.84	0.90	0.91

### B. Dynamic Frequency Stability

To simulate a frequency event, a 150MW machine at bus 8 was dropped 10 seconds into the simulation. This unit represents 12% of the total system generation, roughly equivalent

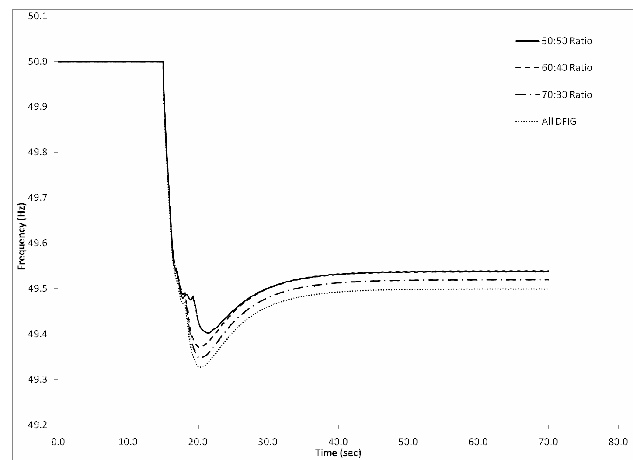


Fig. 3. System frequency for loss of generation event. 50:50 Ratio of DFIG to FSG (solid line), 60:40 Ratio (dashed line), 70:30 Ratio (dot-dashed line), 100% DFIG (dotted line)

to the 15.6% of wind penetration. The machine was kept out of service and the system frequency was monitored.

By varying the ratio of turbine types, the amount of spinning inertia can be increased as more FSGs are added to the system. The Irish grid code specifies that generator action is required in response to an event where the frequency falls below 49.80 Hz [13]. In DFIGs, there will be no response to this frequency dip, since by design, they are not contributing to the system's spinning inertia. As a result, to increase the system's spinning inertia, the ratio was adjusted to include more FSGs. From the steady-state analysis, it was determined that at least a 50:50 ratio of DFIGs to FSGs was necessary to maintain the appropriate voltage levels across the system. Based on this ratio, frequency simulations were carried out at ratios of 50:50, 60:40, and 70:30 of DFIGs to FSGs. A final frequency simulation was also run, where the only type of wind turbine present was the DFIG. The results of this analysis can be seen in Fig. 3.

From Fig. 3 it can be seen that frequency dips further when there are more DFIGs present in the system. The inertial response in these simulations is provided exclusively by the conventional machines and the FSGs. The nadir of the frequency is significantly improved when more FSGs are present in the system. Fig. 3. also demonstrates that the frequency can recover to the same value when the level of DFIGs present in the system is between 50% and 60%. This would imply that for this particular system the optimal mix between DFIGs and FSGs to maintain frequency stability lies between these values. The frequency trace for the case where no FSGs are present has the lowest nadir. This was expected since there were no additional machines providing the system with spinning inertia. The nadir of each frequency simulation can be seen in Table II.

TABLE II  
FREQUENCY NADIR FOR VARYING RATIOS

Ratio (DFIG:FSG)	50:50	60:40	70:30	All DFIG
Nadir (Hz)	49.40	49.38	49.35	49.33

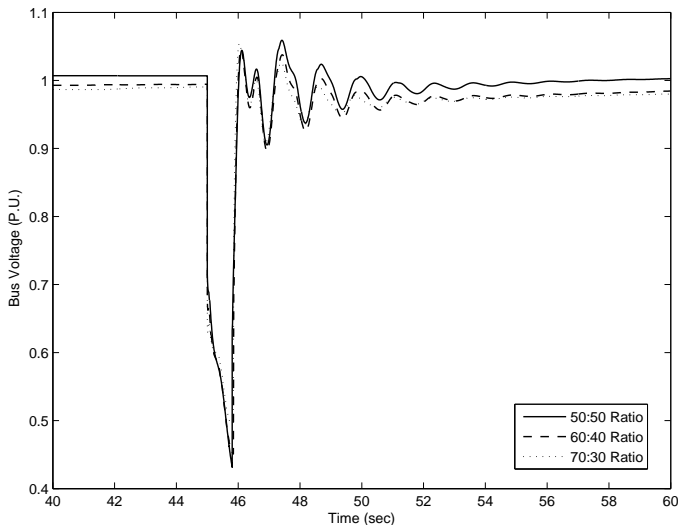


Fig. 4. Voltages at bus 14 with DFIG to FSG ratio. 50:50 Ratio (solid line), 60:40 Ratio (dashed line) and 70:30 Ratio (dotted line)

### C. Dynamic Voltage Stability

The dynamic voltage analysis was carried out by applying a  $0.2j$  line fault at the branch connecting buses 10 and 21. The results of this fault analysis are given in Table III. Beginning from the 50:50 ratio, it can be seen that increasing the ratio of DFIGs in the system by 10% corresponds to a 50ms increase in the critical clearing time of the fault. However, another 10% increase in the level of DFIGs, results in the same critical clearing time. The bus voltages under faulted conditions were plotted using the clearing times from Table III and can be seen in Fig. 4. The voltages were monitored at all of the FSG interconnections. Fig. 4 contains the voltage plots for bus 14, one of the wind farm interconnections. Although there may not be a significant difference in the critical clearing times as the level of DFIGs changed from 60% to 70%, the minimum voltage reached shows significant improvement as can be seen in Table IV.

TABLE III  
CRITICAL CLEARING TIME FOR  $0.2j$  FAULT

Ratio (DFIG:FSG)	50:50	60:40	70:30
Critical Clearing Time (ms)	540	590	590

TABLE IV  
MINIMUM BUS VOLTAGE DURING FAULTED CONDITION

Ratio (DFIG:FSG)	50:50	60:40	70:30
$V_{min}$ (p.u.)	0.4313	0.4507	0.4975

Based on the analysis of dynamic voltage stability the 60:40 ratio and 70:30 ratio provide the system with the most support during faulted conditions. Although the 70:30 ratio improves the minimum voltage dip, the clearing times for system stability remain the same for both ratios.

TABLE V  
ADJUSTED RATIOS FOLLOW PV TRANSFER ANALYSIS

Area	2	3	4	5
Ratio (DFIG:FSG)	63.7:36.3	67.6:32.4	69.4:30.6	37.2:62.8

### V. INCREMENTAL PV TRANSFER CAPABILITY ANALYSIS

From the previous analyses an optimal ratio can be selected in order to provide the system with the greatest levels of voltage and frequency stability. The 60:40 ratio provided nearly the same voltages as the 70:30 ratio for varying wind speeds during the steady-state simulation. It also provided frequency recovery to the same final value of the 50:50 ratio. Finally, in comparison to the 70:30 ratio during faulted conditions it provided the same critical clearing time for the fault. As a result it was determined that the 60:40 ratio would provide the system with the greatest level of voltage and frequency support with a large wind penetration level. By using this ratio as a system set point, i.e. make sure that the system ratio of DFIGs to FSGs was always 60:40, it was felt that this ratio could be modified by identifying particular regions that needed more voltage support compared to others. By shifting the ratio of DFIGs from one area to another the voltage stability of regions with low voltages could be improved. Using the incremental PV transfer analysis tool in PSS/E, the voltage sensitivity of each region was assessed as follows.

Using the four operating areas with wind generation installed in the IEEE 30 bus test system, a “source” area and “sink” area were selected. The “source” area provided generation during the incremental power transfer to the load in the “sink” area. The voltages in both areas were monitored as power was transferred and the MW value that increased the voltages the most in the “sink” area was recorded. This process was completed for all of the wind generation areas in the system and the total transfer capability for each individual area was summed for each case. Areas that saw higher voltages as power was transferred in were identified as regions that should see an increase in the DFIG ratio. This assumption was made based on the fact that DFIGs can be utilized to provide local voltage control through increased reactive power support. An area that could maintain high voltages as power was transferred out maintained the balance in the system ratio of DFIGs to FSGs by decreasing the level of DFIGs in their area.

Using the initial 60:40 ratio, an incremental PV transfer capability analysis was carried out on each wind generation area in the system. The resulting ratios adjusted to improved voltage stability are summarized in Table V. In comparing the voltages the average rose from 1.0308 p.u. with the 60:40 ratio to 1.0376 with the modified ratios, and the minimum voltage in the system rose from 0.91 p.u. to 0.92 p.u.. It is important to note that although the local ratios have changed, the system ratio still remains 60:40 DFIG to FSG. Overall, 27 MW of generation were transferred into areas 2, 3, and 4 creating an increase in the system’s voltage similar to the 70:30 ratio, however the same level of spinning inertia is present in the system allowing for sufficient frequency response. The

main reason behind this result is areas 2, 3, and 4 have a majority of the system's load. The MW transfer allowed for an increased presence of reactive support and an improvement of the system-wide voltage.

## VI. SCOPE FOR FURTHER WORK

Additional studies using this methodology will be applied to the 2013 Irish electric system to determine how the system will respond to large penetrations of wind and whether voltage and frequency stability in the system can be maintained using the ratio of wind turbine types as the main constraint. This study will be completed using historical wind and loading data, capturing the patterns of power use in the electricity system. The new wind farms will also be sited at locations that have been identified as high value wind resource regions, i.e., they have high average wind speeds leading to increased capacity factors for the sites. This study on the 2013 Irish electricity system will also include a complete dynamic analysis using actual dynamic data for the machines present in the system.

## VII. CONCLUSION

The ratio identified in this study is unique to the conditions of this test system. The methodology established for identifying the optimal ratio of DFIGs to FSGs can be applied to other systems. By treating the issue of voltage stability as a local issue and the need for spinning inertia as a system issue, a penetration ratio was identified for the IEEE 30 bus test system, that provided improved voltage support without sacrificing the frequency response of the system. As wind penetration continues to grow, the issues of voltage stability and frequency stability will become more crucial, especially in smaller power systems where a balance between the two is essential. By identifying where voltage control is a priority, DFIGs can be strategically placed to minimize the effects of a fault, while the FSGs can provide the system with an improved frequency response.

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