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Innovation in Power, Control, and Optimization: Emerging Energy Technologies

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Chapter 6 Dynamic Analysis and Stability Improvement Concerning the Integration of Wind Farms: Kurdistan Electric Network Case Study

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ABSTRACT

This chapter presents an overview of key issues and technical challenges in a regional electric network, following the integration of a considerable amount of wind power. A brief survey on wind power system, the present status of wind energy worldwide, common dynamic models, and control loops for wind turbines are given. In this chapter, the Kurdistan electric network in the Northwest part of Iran is introduced as a case study system, and an analytical approach is conducted to evaluate the potential of wind power installation, overall capacity estimation, and economic issues, based on the practical data. Then, the impact of high penetration wind power on the system dynamic and performance for various wind turbine technologies is presented. The stability of integrated system is analyzed, and the need for revising of conventional controls and performance standards is emphasized. Finally, a STATCOM-based control approach is addressed to improve the system stability.

INTRODUCTION

Conventional energy sources such as fossil fuels and uranium reserves are limited and adversely impacts on environment, therefore greet interest for utilization of renewable energy has been established. For recent expansion of renewable energy applications, wind energy generation among other renewable energies has been experiencing a rapid growth. As the use of wind power units increases worldwide, there is a rising interest on their impacts on power system dynamic/control and finding appropriate solutions. The recent investigation studies indicate that relatively large scale wind generation affects the power system frequency and voltage regulation, as well as other control and operation issues. This impact may increase at the penetration rates that are expected to be high in the next several years. On the other hand, most of existing wind turbine technologies cannot provide necessary control capabilities for the regulation issue. The power system control of the future will require a high degree of flexibility and intelligence to ensure that it can continuously balance fluctuating power and regulate frequency/voltage deviation caused by renewable energy sources such as wind (Bevrani, et al., 2011).

This chapter presents an overview of new dynamical challenges in regional electric networks, following a high penetration of wind power. The Kurdistan electric network in Iran is considered as a case study. Mountainous environment, costly process for electricity production from conventional sources, and numerous windy areas make Kurdistan as an appropriate region for installation of wind farms. In this work, an analytical approach is conducted to evaluate the potential of wind power installation and overall capacity estimation, and to study economic issues based on the practical data.

The impact of high penetration wind power on the system dynamic and performance for different wind turbine technologies including fixed-speed induction generator (FSIG), doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) is presented. Using DIgSILENT simulation software, the stability of the integrated system is re-analyzed, and the need for revising of conventional controls and performance standards is emphasized. Finally, a control approach to improve the system stability using static synchronous compensator (STATCOM) and energy storage devices is addressed. This work is supplemented by some nonlinear simulations on the Kurdistan power system case study using real data and parameters.

In the next section, a background with a brief literature review is presented. In section 3, an overview of wind energy status around the world and Iran is provided. Section 4 presents a discussion about wind power systems and the main control schemes. Section 5 determines the potential of Kurdistan province for wind power generation. In section 6, a preliminary study on wind energy costs in Kurdistan is performed. Section 7 presents a dynamic analysis on the impact of a high wind power penetration on the Kurdistan electric network and introduces an appropriate control solution for its stability improvement. Finally, conclusion and future research directions are presented in sections 8 and 9, respectively.

BACKGROUND

In order to clarify the interaction behavior between wind farm(s) and the power system, building of an effective dynamic model for wind power systems (WPSs) is needed. Model simplifications and some comparisons between different types of WPSs and wind farm equivalent models are presented in recent performed research works (Mansouri, et al., 2004; Ekanayake, et al., 2003; Slootweg, et al., 2003; Akhmatov, et al., 2006; Fernandeza, et al., 2006; Ledesma & Usaola, 2005).

The role of WPS control strategy to qualify system output and stability augmentation is studied in many papers. Optimization control, power smoothing and voltage control of WPSs are most important topics of related new research areas (Senjyu, et al., 2006; Wang & Chang, 2004).

Increasing the penetration of wind turbine generators in a power system may affect the system security/stability limits, frequency, voltage and dynamic behavior (Muyeen, et al., 2009; Bevrani, 2009; Slootweg, 2003; Bevrani, Tikdari, & Hiyama, 2010). This effect can be mostly caused by fluctuation of wind power. The impacts of wind turbines on the power system frequency and voltage have been studied in many research works (Jowder, 2009; Radics & Bartholy, 2008; Bevrani & Tikdari, 2010). Power system frequency response model in the presence of high wind power penetration, frequency control issue, and a comprehensive survey with some new perspectives are already well addressed (Bevrani & Hiyama, 2011; Bevrani, Ghosh, & Ledwich, 2010; Bevrani, Daneshfar, & Daneshmand, 2010).

The effects of DFIG and induction generator type of WPSs on the voltage transient behaviors are explained and the disadvantages of the induction generator type are shown in (Nunes, et al., 2004). The loadability of various types of WPSs is studied and it is shown that the DFIG has larger loadability than induction generators (Bevrani & Tikdari, 2010). Frequency nadir in the presence of different types of the WPSs has been also compared in (Erlich, et al., 2006; Gillian, et al., 2005). As argued in the mentioned references, wind turbines affect frequency behavior because they add amount of inertia to the power system. Both stator and rotor windings of induction generator type of WPSs are directly connected to the power grid, but in DFIG type, only stator is directly connected and the rotor is linked through a power electronic type converter. The induction generator WPS in turn adds much inertia than DFIG in the power system; and in conclusion, the induction generator WPS frequency response is better than systems with DFIG type in the same conditions.

Continuous increase of installed wind power during recent years has forced the system operators and responsible organizations to tighten the performance standards and connection rules – known as *grid code* - in order to limit the effects of wind power penetration on the power system performance and stability.

Interconnection procedures and standards need to be reviewed to ensure that the new operating control schemes and their responses are in a consistent manner to all power generation technologies, including wind generating units as variable generation technologies. The revised operating performance standards require that most type of power plants support the electricity network throughout their operation. Important key issues can be considered as steady state and dynamic active/reactive power capability, continuously acting frequency/voltage control and fault ride through behavior. Some commonly used turbine designs have some limits in terms of achieving grid code compliance in several countries. For the wind farms containing these turbines, additional equipments are needed (Maibach, et al., 2007).

Variable generation technologies generally refer to generating technologies whose primary energy source varies over time and cannot reasonably be stored to address such variation. Uncertainty and variability are two major factors of a variable generator that distinguish it in conventional forms of generation and may impact the overall system planning and operations (Bevrani & Hiyama, 2011).

In order to specify wind power potential in a particular site, a long-term record of wind speed has to be statistically analyzed. There are several studies related to the determination of wind characteristics and wind power potential in many countries over the whole world (Radics & Bartholy, 2008; Elamouri, Ben, & Amar, 2008; Al-Abbadi, 2005; Jowder, 2009; Ucar & Balo, 2009; Weigt, 2009)

State of Wind Power Generation

At present, wind power has effective impact on energy markets. In 2009, more than 38.3 GW of new wind power capacity was installed around the world that bringing the total installed capacity up to 158.5 GW. The main markets driving this growth rate are Asia, North America and Europe. The top five countries in wind energy installed capacity in 2009 were US with 35064 MW (22.1%), PR China with 25805 MW (16.3%), Germany with 25777 MW (16.3%), Spain with 19149 MW (12.1%), and India with 10926 MW (6.9%); while the total installed wind power in the rest of world was 41784 MW (26.4%) (GWEC, 2010).

Similar to the most countries in the Middle East and Africa, contribution of the wind energy for production of electricity in Iran is relatively low. The total installed capacity of wind turbine in Iran by 2010 is less than 200 MW. There are many suitable areas for installing wind turbines in Iran; however as depicted in Table 1, the major installed wind power is centralized in Manjil and Binalud areas.

Because of existing high sources of oil and gas in a relatively low price in Iran, most of electricity has been produced by fossil fuel in the past. However, nowadays for many reasons, as well as other countries there is a great concern towards renewable energies like wind and solar. The government and other responsible organizations have put some efforts to expand wind and solar farms in different parts of country. Currently, the potential for wind power generation is estimated to be more than 6500MW.

Wind Power Controls

A WPS transforms the energy presented in the belonging wind into electrical energy. A general scheme of this system is shown in Figure 1a. Wind energy is transformed into mechanical energy by wind turbine units. Based on rotational speed, the wind turbines can be split into two types:

- 1. Fixed speed wind turbine (FSWT)
- 2. Variable speed wind turbine (VSWT)

Major characteristics of the FSWT are brushless and rugged construction, low cost and simplicity. The main advantage of the VSWT is that more energy can be extracted for a specific wind speed regime. In addition, the mechanical stress is less; because the rotor acts as a flywheel (Slootweg, 2003). Common VSWT structures are known as DFIG and the PMSG. A FSWT is usually directly equipped with a grid coupled squirrel cage induction generator whose speed variations are limited.

The power extracted from the wind energy by a wind turbine can be expressed as follows (Heier, 1998; Bansal, et al., 2002):

$$P_m = \frac{1}{2} \rho A V_w^{\ 3} C_p(\lambda,\beta) \tag{1}$$

where, P_m is the power extracted from the wind, p is the air density (Kg/m³), A is the rotor disc area (m²), V_w is the wind speed (m/s), and C_p is a power coefficient which is a function of the tip speed ratio λ and the pitch angle of rotor blades β . The tip speed ratio λ is defined by

$$\lambda = \frac{\omega_r R}{V_w} \,. \tag{2}$$

Area	No. of turbines	Power (KW)		
	27	300		
	2	500		
Binalud	18	550		
	1	600		
	64	660		
Total	112	61840		
Manjil	43	660		
Total	43	28300		

Table 1. Wind power in Binalud and Manjil areas



Figure 1. Wind energy conversion system; a) General scheme of WPS, and b) Drive train model

where, ω_r is mechanical angular velocity of the turbine rotor and R is the blade radius of the wind turbine.

As shown in Fig. 1b, the drive train model of wind turbines is usually represented by two mass models (Slootweg, Haan, Polinder, & Kling, 2003; Slootweg, Polinder, & Kling, 2003):

$$T_w - T_m = J_r \frac{d\omega_r}{dt}$$
(3)

$$T_m = D_{mc}(\omega_r - \omega_g) + K_{mc} \int (\omega_r - \omega_g) dt$$
(4)

$$T_m - T_g = J_g \frac{d\omega_g}{dt}$$
⁽⁵⁾

where, J_r , and J_g are inertia of wind turbine and generator, ω_g is the rotor speed, T_m is the mechanical torque from the generator shaft, T_g is

the generator electrical torque. Finally, K_{mc} and D_{me} are the stiffness and damping of mechanichal coupling, repectively.

Power extracted from a wind turbine can be controlled in two states, in above and below rated wind speed of wind turbine. In the above rated wind speed, a blade pitch angle controller reduces the power coefficient and thus the power extracted from the wind. The pitch controller limits the generator's speed to a rated value ($\omega_{gen, rated}$) by adjusting the pitch angle (β).

Second control state (below rated wind speed) exists only for the VSWT generator type. The aim is to control the rotational speed to follow the maximum power point trajectory (MPPT), when wind speed is in change. Since, precise measurement of wind speed is difficult, for maximum power point tracking operation, it is better to use the rotor speed as a control input instead of wind speed.

Modeling and Control of DFIG

The control strategy that generally applied to control of VSWT is based on vector control techniques. An overview of dynamic model for DFIG wind turbine and the associated control system is shown in Figure 2a (Hansen, et al., 2003; Hansen, et al., 2004).

The rotor-side converter operates in a stator flux reference frame that decomposes the rotor current into active power (q-axis) and reactive power (d-axis) components. A fast inner current control loop controls rotor current in d- and qaxis and a slower outer control loop regulates active and reactive powers. The MPPT unit provides the reference signal $P_{Grid,ref}$ for the active power, while the reactive power $Q_{Grid,ref}$ is typically fixed at zero.

The grid-side converter controller operates in a grid side converter voltage oriented reference frame (DIgSILENT GmbH, 2003). Active and reactive components of the grid-side converter currents are controlled by the fast inner control loop. The slower outer control loop determines the q-current set point, which regulates the DC-voltage to a pre-defined value. For achieving unity power factor operation of converter, it is sufficient that q-current to be regulated to zero.

Figure 2. Overall structure and main control loops of VSWT systems a) DFIG, and b) PMSG



Modeling and Control of PMSG

An overview for dynamic model of the PMSG wind turbine and its control system is shown in Figure 2b. The control structures and related concepts are well discussed in the recent published works (Conroy & Watson, 2008).

At the generator-side converter, AC-voltage and active power are regulated (reactive power regulation is optional). The grid-side converter operates in a stator voltage oriented reference frame. A fast inner control loop regulates the dand q-axis current components of the grid-side PWM-converter. Current references are defined by a slower outer control-loop regulating DC-voltage of the intermediate DC-circuit and reactive power.

Wind Energy Potential Assessment in Kurdistan

In this section, to determine the potential of wind power generation the hourly measured wind speed data over a period of almost 5 years between 2004 and 2008 from 6 stations in Kurdistan, at 10 m height that obtained from Kurdistan Meteorological Organization are statically analyzed. Extrapolation of the 10 m data, using the *power law*, is used to determine the wind data at upper heights. The power law used in this study is as follow:

$$\frac{V_{H}}{V_{ref}} = \frac{Ln \frac{H}{Z_{0}}}{Ln \frac{H_{ref}}{Z_{0}}}$$
(6)

where, V_{H} is the wind speed at height H, V_{ref} is the wind speed at height H_{ref} , and Z_{0} is surface roughness length.

Gilbert (2004) explains the roughness classifications and roughness lengths. The roughness length for water surface (Class 0), open areas with a few windbreaks (Class 1), farm land with some windbreaks more than 1 km apart (Class 2), urban districts and farm land with many windbreaks (Class 3), and dense urban or forest (Class 4) are determined as 0.0002 m, 0.03 m, 0.1 m, 0.4 m, and 1.6 m, respectively. In this work, since the studied stations are located in near cities or even inside cities and due to mountainous environment of Kurdistan, the roughness lengths for most stations are fixed at 1 (Class 1).

Site Selection

Gillbert (2004) presented a standard for using in site selection in a wind farm installation procedure. Based on this standard and according to the annual mean wind speed from 2004 to 2008, among considered six cities of Kurdistan (Bijar, Qorveh, Marivan, Saqez, Sanandaj, and Divandarreh), regions of Bijar and Divandarreh are determined as more fair places for wind farm installation (Table 2).

Monthly Variation of Mean Wind Speed

Figure 3 shows monthly variation of mean wind speed for selected two sites (Divandarreh and Bijar). In both stations, the highest monthly wind speed occurs in March. In Bijar, the lowest wind speed happens in January; while for Divandarreh it happens in December.

Wind Rose Diagram

The direction of the wind is taken into consideration for the sake of installing the wind turbines in a wind farm. The wind rose diagram illustrates the wind direction. Figure 4 shows the wind rose diagram for Bijar and Divandarreh, using the WRPLOT software. Based on these diagrams, the wind mainly blows to the north side of city in Bijar, however for region of Divandarreh, the wind blows mainly in direction of east.

Wind power class	Annual mean wind speed (^m /s)	Height from sea level (m)	Longitude		Latitude		Location
			Min	Deg	Min	Deg	
Class 3	6.73	1883.4	37	47	53	35	Bijar
Class 1	5.58	1906.0	48	47	10	35	Qorveh
Class 1	3.06	1286.8	12	46	31	35	Marivan
Class 1	4.25	1522.8	16	46	15	36	Saqez
Class 1	3.40	1373.4	0	47	20	35	Sanandaj
Class 3	6.72	2142.6	55	46	4	36	Divandarreh

Table 2. Annual mean speed at 50 m height from the ground for different locations

Wind Power Installation and Economic Issues

In this section, the economic evaluation for installing four wind turbines in capacity of 0.8, 1.5, 2 and 3 MW, for Bijar and Divandarreh are

estimated using the *levelised cost of electricity* (LCOE) method. For this purpose, the weibul distribution is obtained for these sites. Wind frequency distributions for Bijar and Divandarreh at 60 m height are shown in Figure 5.

Figure 3. Average wind speeds for different months based on the recorded data from 2004 to 2008, for a) Divandarreh, and b) Bijar



Wind Power Calculation

Calculation of annual energy production from a WPS in a given site requires the considered turbine power curve with weibul distributions of wind speed for the site. In this study, Enercon E-53 (800 KW), Nordex 77 (1.3 MW), Gamesa G90 (2 MW), and Vestas V112 (3 MW) wind turbine technologies are considered. The information related to these wind turbines can be obtained from their manufactures web sites (www.vestas. com, www.nordex-online.com, www.enercon.de, and www.gamesa.es).

Capacity factor (CF) is one of important indicators for assessing the performance of a wind turbine. The capacity factor of a WPS at a given site can be defined as

$$CF = \frac{E_p}{E_{rated}} \tag{7}$$

where, E_p is the produced energy by the system in the specific period, and E_{rated} is the energy that

Figure 4. Wind rose diagrams based on the recorded data from 1992 to 2006, for a) Bijar, and b) Divandarreh





Figure 5. Frequency distributions of wind speed at 60 m height for a) Bijar, and b) Divandarreh

(b)

could be produced by the system, while the machine operates at its rated power in the same period.

The CF can be written as (Jangamshetti & Rau, 1999):

$$CF = \frac{1}{V_R^3} \int_{V_C}^{V_R} V^3 f(V) dV + \int_{V_R}^{V_F} f(V) dV$$
(8)

where, the v_c is the cut-in wind speed of wind turbine generator in m/s, the v_R is the rated wind speed of wind turbine generator in m/s, and v_F is the cut-out wind speed of wind turbine generator in m/s. The above equation can be calculated as

$$CF = \left(\frac{V_c}{V_R}\right)^3 e^{-\frac{|V_c|}{C}|_K} + \frac{3\Gamma(\frac{3}{K})}{K\left(\frac{V_R}{C}\right)^3} \left[\gamma\left(\frac{V_R}{C}\right)^K, \frac{3}{K}\right) - \gamma\left(\frac{V_c}{C}\right)^K, \frac{3}{K}\right) - e^{-\frac{|V_r|}{C}|_K}$$
(9)

where, γ is the incomplete gamma function (Jangamshetti & Rau, 1999; Suresh, et al., 2001).

Energy Cost Analysis

The LCOE for WPSs can be described as the ratio of the total annualized cost to the annual electricity produced by the system. The following expression can be used to estimate the LCOE delivered by a WPS (Gokcek & Genc, 2009; Nouni, et al., 2006),

$$LCOE = \frac{C_{wt}R_{wt} + C_{bb}R_{bb} + C_{ci}R_{ci} + C_{in}R_{in} + C_{mise}R_{mise} + C_{om}}{E_{p}}$$
\$/KWh (10)

Here, the E_p is annual energy production by delivered WPS, C_{wt} is cost of wind turbine, C_{bb} is cost of battery bank, C_{ci} is the civil work and installation cost, C_{in} is cost of the inverter, C_{misc} is miscellaneous costs such as connecting cables, control panel and other components; and C_{om} is annual operation and maintenance cost. The R_{wt} , R_{bb} , R_{ci} , R_{in} and R_{misc} present the capital recovery factors (R) for wind turbine, battery bank, civil work and installation, inverter and other miscellaneous components, respectively.

For a given discount rate (r) and useful system lifetime (n), the capital recovery factor can be defined as follows:

$$R = \frac{(1+r)^n r}{(1+r)^n - 1} \tag{11}$$

A break-up of relative costs for different components of a typical WPS can be easily obtained (Nouni, et al., 2006). The cost evaluation is made by means of this cost break-up for all WPSs. A typical cost table for different wind power technologies is presented (Sathyajith, 2006). A specific cost of WPS can be calculated as follows,

$$C_{WPS} = I_{WPS} P_R [\$]$$
(12)

Where, the I_{WPS} is the specified cost of the WPS.

The estimation of the KWh cost of energy delivered by the WPS operating at the given sites has been done under the following assumptions:

- 1. The lifetime of the WPS (n) is assumed to be 25 years.
- 2. The discount rate (r) is taken as 12%.
- Operation and maintenance cost (C_{om}) is considered to be 2% of initial capital cost of the WPS project (Nouni, et al., 2006)
- 4. Useful lifetime for the battery bank and inverter are assumed to be 7 and 10 years, respectively (Nouni, et al., 2006).
- It is assumed that the WPS production is equal to the amount of energy output in each year during its useful lifetime (Türksoy, 1995).

The results of cost analysis performed in this study for the WPS with different size ranges are presented in Table 3. From this table, it is seen that the predicted maximum and minimum values regarding electricity cost per kWh for each WPS are calculated by taking into account the limit values of the band interval of WPS specific cost. The minimum levelised cost of electricity is calculated that WPS- Vestas V112 (3 MW) is 0.074 \$/kWh, while its maximum value is 0.118 \$/kWh. These values are the predicted lowest values for WPS in both cases of Divandarreh and Bijar.

According to the all band intervals, the highest electricity costs are calculated in the case of WPS-Gamesa G90 (2 MW) in Bijar, as 0.116 \$/kWh for lower-limit and as 0.186 \$/kWh for upper-

Table 3. Cost analysis per kwh for WPS in Bijar and Divandarreh

WPS	Divandarreh			Bijar			
	CF	Cost (\$/kwh)		CF	Cost (\$/kwh)		
		Min	Max		Min	Max	
Enercon E-53 (0.8 MW)	0.2746	0.088075	0.140919	0.2677	0.090345	0.144552	
Nordex 77 (1.5 MW)	0.2614	0.092522	0.148035	0.2544	0.095068	0.152109	
Gamesa G90 (2 MW)	0.2151	0.112437	0.1799	0.2079	0.116331	0.18613	
Vestas V112 (3 MW)	0.3286	0.073601	0.117762	0.3286	0.073601	0.117762	

limit. As seen from the calculation of annual energy production, the WPS of 3 MW rated power among the WPS considered in the study is most attractive in terms of the levelised unit cost.

Dynamic Impacts Analysis and Stability Improvement

Case Study

In this section, transient stability of Kurdistan electric network in the presence of two wind farms in Bijar and Divandarreh are analyzed. A combination of FSIG and DFIG turbines are used in the mentioned wind farms. Single line diagram of Kurdistan network with wind farms is shown in Figure 6. Two 50-MW wind power plants are added to 63 KV bus, near to the cities of Divandarreh and Bijar. It is noteworthy that in Kurdistan, only there is one conventional power plant (Sanandaj Power Plant) with above 200 MW. Detailed system information and power system parameters are given in (Saleh, 2010).

Simulation Results

In this study, the power system simulation program, Power Factory (DIgSILENT), is used as a suitable tool for power system modeling and simulation. In the simulation environment, the conventional power plant exciter is represented using the standard model EXST1; the power system stabilizer is represented using a dual-input power system stabilizer model (PSS2A), and governor-turbine is represented by the standard model GAST. Load model is represented using a static model. The voltage dependencies on active and reactive powers are considered as 1 and 2, respectively.

For transient stability investigation, a three phase short circuit with duration of 0.34 sec is considered in an important location. The fault location is shown in Figure 6. Figure 7 depicts

Figure 6. Single-line diagram of the Kurdistan electric network with two wind farms





Figure 7. System response following a three phase short circuit

system response including voltages at Divandarreh and Bijar buses (connected to the wind farms), rotor angle of Sanandaj power plant, WPS's speed, and active and reactive powers.

As discussed, the WPSs commonly use the induction generators to convert the wind energy into electrical energy. The induction generators act as reactive power consumers. Therefore, the system voltage would be affected in the presence of wind turbines, especially in the case of fixedspeed type of WPSs. This issue can be also seen from simulation results shown in Figure 7. A decrease in related bus voltages with a permanent oscillation in active power and speed of aggregated generators are indicated. It is shown that in view point of reactive power compensation, the Kurdistan grid is much weaker in Bijar than Divandarreh area.

Stability Improvement

For the sake of system frequency and real power compensation in the presence of WPSs, several control approaches are already presented (Bevrani & Hiyama, 2011; Bevrani, Daneshfar, & Daneshmand, 2010). In order to reactive power compensation, which is the main control issue in the present work, traditionally the capacitor banks are suggested to use. However, it is noteworthy that capacitor banks cannot provide dynamic compensation for events such as the sudden drop of voltage. In response to above challenge, to improve stability after grid disturbances such as short circuit faults, the STATCOM technology as a powerful control tool is examined.

The STATCOM is extensively being used in power systems because of their ability to provide flexible power flow control (Muyeen, et al., 2005). The main motivation for choosing STATCOM in wind farms is their ability to provide bus bar system voltage support either by supplying and/ or absorbing reactive power into the system. The applicability of a STATCOM in wind farms has been investigated and the results from early studies indicate that it is able to supply reactive power requirements of the wind farm under various operating conditions, for improving transient stability (Chun, et al., 2000), as well as enhancement of the steady-state stability margin (Saad-Saoud, et al., 1998). Regarding the grid codes mentioned in Section 2, it is also investigated that the medium voltage STATCOM technology which adds the missing functionality to wind farms in order to become grid code compliant. Especially, the voltage control and the fast dynamic behavior during balanced as well as unbalanced grid faults (fault ride-through) are highlighted (Maibach, et al., 2007).

An appropriately sized STATCOM can provide the necessary reactive power compensation when connected to a weak grid. Also, a higher rating STATCOM can be used for efficient voltage control and improved reliability in the interconnected grid with wind farms. However, it is noteworthy that the STATCOM rating is limited by economic issues. The location of STATCOM is generally chosen to be a point in the system which needs reactive power. Simulation results show that STATCOM provides effective voltage support at the bus which is connected to the Bijar wind farm. That is why, for stability improvement of the example at hand, a 30-Mvar STATCOM is connected to 63 KV bus, near to the Bijar wind farm.

Another reason for choosing the mentioned place is that the location of the reactive power support should be as close as possible to a point at which the support is more needed. Furthermore, in the present case study, in addition to the losses reduction and increase of power transfer capability, the location of the STATCOM to the center of averaged load is more appropriate because the impact of voltage change is more significant at this point.

But it is notable that the shipping of reactive power at low voltages in the system running close to its stability margin is not very efficient. Also, the total amount of reactive power transfer available will be influenced by the transmission line power factor. Hence, the compensation devices are always kept as close as possible to the center of equivalent load as the ratio $\Delta V/Vnominal$ will be higher for the load bus under fault conditions (Prabhakar, 2008).

The system response in the presence of STAT-COM for the accrued fault is shown in the Figure 8. Results show a considerable improvement in transient stability. The transient behavior of wind farms are also improved by injecting large amounts of reactive power during the fault recovery. Flexibility in voltage control for power quality improvement, fast response, and applicability for use with high power/load fluctuation are the main advantages of the proposed STATCOM-based control strategy.

FUTURE RESEARCH DIRECTIONS

Some important research needs in future can be summarized as follows:



Figure 8. System response with STATCOM support

- Coordination between STATCOM, energy storage devices, power system stabilizers, and excitation controls of conventional power plants can be considered as an important topic for further research in the field of power systems stability improvement. Determine the proper location and size optimizing of STATCOM is another research topic that should be considered.
- A more complete dynamic model is needed in order to stability analysis and control synthesis in interconnected power systems with a high degree of wind power penetration. Further study is needed to define new grid codes for contribution of large WPSs into the power system stability/performance improvement. Future grid codes should clearly impose the requirements on

the regulation capabilities of the active/reactive power of WPSs.

- Control performance standards compliance verification remains a major open issue for wind power units. This concerns specific WPS capabilities and will require the development of additional standards for testing, from the level of the component up to the entire WPS.
- Advanced computing algorithm and fast hardware measurement devices are also needed to realize more effective optimal/ adaptive control schemes for the power systems with a high penetration of WPSs.
- Since, naturally the wind power is stochastic, still it is difficult to straightly use wind turbine kinetic energy storage in the regulation tasks such as frequency control. The contribution of WPSs in active power and frequency regulation refers to the ability of these units to regulate their power output (Bevrani, et al., 2010). More effective practical algorithms and control methodologies are needed to perform these issues. Further studies are needed to coordinate the timing and the size of the kinetic energy discharge with the characteristics of conventional plants.
- To allow the increase of wind power penetration, a change in regulation reserve policy may be required. In this direction, in addition to the deregulation policies, the amount and location of wind turbines, generation technology, and the size and characteristics of the electricity system must be considered as important technical aspects.
- Continuous development of communications and information technology, as well as market and regulatory frameworks for generation and consumption is necessary for a power system with intelligent electricity meters and intelligent communications (Bevrani, et al., 2011).

The wind turbine units must meet technical requirements with respect to the voltage, frequency, ability to rapidly isolate faulty parts from the rest to the network, and have a reasonable ability to withstand abnormal system operating conditions. They could be able to function effectively as part of the existing electricity industry particularly during abnormal power system operating conditions when power system security may be at risk.

High wind power penetration, particularly in the locations far away from major load centers and existing conventional generation units increases the risk of tie-line overloading, and may require network augmentation, and possibly additional interconnections to avoid flow constraints. With increasing wind power penetration, the grid codes for the connection high wind turbines capacity should be also updated (Bevrani, et al., 2011).

• Furthermore, the updating of existing emergency frequency control schemes for N-1 contingency, economic assessment/ analysis of the frequency regulation prices, further study on frequency and voltage stability using dynamic demand control and ratios of wind turbine technologies, and quantification of reserve margin due to increasing wind power penetration (Bevrani, et al., 2010) can be considered as other important research needs in future.

CONCLUSION

In this chapter an intensive overview of wind energy status around the world and Iran is presented. The dynamic model and the main control loops of wind turbine technologies are explained. As a practical case study, the wind power potential, economic issues, and technical challenges for a high penetration of wind power in Kurdistan electric network are discussed. The possibility of connecting a STATCOM to the wind power system in order to provide an efficient control method is explored. The STATCOM as a pure static device with no switched passive components, which provides outstanding performance for both steady state and dynamic operation is used as a suitable control solution to decrease the undesirable impact of wind power plants on the transient stability and to improve the system performance. It is shown that the proposed STATCOM based design strategy provides dynamic voltage control and power oscillation damping, and improves the Kurdistan network transient stability.

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KEY TERMS AND DEFINITIONS

Power System Stability: The ability of a power system to regain a state of operating equilibrium after being subjected to a physical disturbance, with most systems indices (voltage, angle, and frequency) bounded. Power system stability can take three different forms of rotor angle, voltage, and frequency stabilities.

Power System Control: This term is used to define the application of control theory and tech-

nology, optimization methodologies, and expert/ intelligent systems to improve the performance and functions of power systems during normal and abnormal operations.

Capacity Factor: Capacity factor is defined as the ratio of the average power output to the rated output power of the wind energy converter system.

Wind Rose Diagram: The wind rose diagram illustrates the wind direction in a given site.

Fixed Speed Wind Turbine: Wind turbine that is directly connected to the grid with a small speed variation of its rotor.

Variable Speed Wind Turbine (VSWT): This type of wind turbine is decoupled from the grid through a power electronic converter and the rotor acts as a flywheel.

Static Synchronous Compensator (STAT-COM): A technology being extensively used as dynamic shunt compensator for reactive power control in transmission and distribution system.

Levelised Cost of Electricity (LCOE): The LCOE for WPSs can be described as the ratio of the total annualized cost to the annual electricity produced by the system.

Weibull Distribution: The probability distribution, which is widely used to describe the long-term records of wind speeds.