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MODELING WIND FARMS IN POWER SYSTEM SIMULATION STUDIES: A REVIEW

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Abstract

The penetration of wind energy in power systems increasing and has began to influence overall power system behavior. This situation has to be investigated in order to sustain reliable power system operation. However, adequate models of power system components and wind energy conversion systems are needed to use in grid investigation studies and simulations. In this study, a review is given of the modeling issues about grid with wind power.

RÜZGAR SANTRALLERİNİ ELEKTRİK ŞEBEKE SİMÜLASYONLARINDA MODELLEME: BİR DERLEME

Özetçe

Rüzgar enerjisinin elektrik güç sistemi içindeki katılımı hergeçen gün artmakta ve elektrik güç sisteminin tüm işletme karakterini etkilemeye başlamaktadır. Bu durum elektrik güç sisteminin güvenli işletmesinin devamının sağlanması adına araştırılmalıdır. Ancak elektrik şebekesi ile ilgili yapılacak bu çalışma ve simülasyonlar için, rüzgar enerjisi dönüşüm sistemleri ve elektrik güç sistemi elemanlarının geçerli ve yeterli modellerine ihtiyaç duyulmaktadır. Bu çalışmada; rüzgar enerjisi barındıran elektrik güç sisteminin modellenmesi hakkında yapılan çalışmalar gözden geçirilmiştir.

Anahtar Kelimeler: Elektrik Güç Sistemi, Rüzgar Enerjisi Dönüşüm Sistemi, Modelleme, Simülasyon.
Keywords: Grid, Wind Energy Conversion Systems, Modeling, Simulation.

1. INTRODUCTION

The amount of grid connected wind power has increased enormously during last decade. Penetration of wind power with other distributed generation sources has been reducing the amount of power supplied from conventional power plants. Large wind farms are being connected to the high voltage transmission lines all over the world. The penetration of wind energy in power systems will increase and they may begin to influence overall power system behavior. This situation has to be investigated in order to sustain power system operation. However, adequate models of power system components and wind energy conversion systems (WECS) are needed to use in grid investigation studies and simulations.

Power system simulation packages are commonly used for power system operational studies by Transmission System Operators (TSO). All power system components are modeled by reasonably accurate and low-capacity-demanding models. Simplifications are done for every component model used in the system to get convenient computation time and results. Models of the new types of generation units, like wind turbines, have to comply with this requirement. There are simulation packages, which in principle can describe a complete wind turbine with all units. However, the turbine description used in those programs can not be viable in grid simulations packages because of high computational burden and can not be used to represent wind farms containing hundred of wind turbines in grid simulations without proper simplifications.

In order to obtain adequate models of power system components and WECS, studies have been performed with the help of simulation platforms. In this study; a review of modeling wind farms in power system simulation studies will be given with brief statements.

2. GRID CONNECTION OF WIND FARMS

The wind farms have different impacts and functions on the performance of the grid than conventional power plants, because of variation of wind speed in time. The increasing percentage of WECS in electrical power production has amplified the need to address grid integration concerns. Grid codes, determining the requirements about grid connection of wind farms, have been developed by research groups. These grid codes are being updated due to the new technologies and grid connection studies. Also TSO need simulation tools and scientific practices before wind power-power system integration to guarantee reliable operation of the system with wind power. Power system reliability consists of system security and adequacy.

2.1 Grid Codes

At the end of the 1980s, distribution network companies in Europe started to develop their own interconnection rules or standards. In the beginning, each network company that faced an increasing amount of interconnection asks the wind farms to follow its own rules. During the 1990s, these interconnection rules were harmonized on a national level, like in Germany and Spain.

In order to assure reliable operation, TSO demanded high short-circuit power capability at wind farm connection buses, like at least 20 times greater than the wind farm nominal power. These regularities impede further penetration of wind power because of power system operational precautions.

Modern MW wind turbines currently replace a large number of small wind turbines and there is a significant attention to offshore wind farms, mainly because of higher average wind speed and no space limitations. Large power rated wind farms are started to operate in superior power systems and more large power rated wind farms are in construction or in the planning stage all over the world.

However, in order to achieve objectives as continuity and security of the supply, a high level of wind power into electrical network posses new challenges as well as new approaches in operation of the power system.

Therefore countries started to issue dedicated "grid codes" for connecting the wind turbines/farms to the electrical network addressed to transmission and/or distributed system.

These requirements have focus on power controllability, power quality, low voltage ride-through (LVRT) capability and grid support during network disturbances. Grid code regulations often contain costly and demanding requirements for wind farm operators due to the increase in share of wind farms in power production. Large wind farms connected at the transmission level have to act as a conventional power plant and participate in primary (local) and secondary (system level) frequency/power control.

2.2 Need for Accurate Models

Since these demanding requirements can limit the penetration of the wind power in a given area, it was stated that grid codes and other technical requirements should reflect the true technical needs for system operation and should be developed in cooperation between TSO, the wind energy sector, government bodies, universities and research institutes [1-2]. To facilitate the investigation of the impact of a wind farm on the dynamics of the power system to which it is connected, an adequate model is required [3].

According to the grid codes, wind farm operators have to provide evidence of the fulfilment of LVRT capability requirements for their particular case. For single wind turbines it may be sufficient to present a certificate for LVRT capability, but large power rated wind farms need to be investigated by simulations, which include steady state as well as dynamic studies. Besides, fulfilling grid requirements must be monitored continuously after installation [4].

3. MODELING WIND FARMS

Many studies have been performed on grid connected wind farms and related power system issues. Different techniques and models have been used for determining problems; the impacts of wind farms on technical and operational characteristics of power systems and technical requirements for wind farm-grid connections were analyzed.

Slootweg et.al. and Petru & Thiringer focused on deriving a representation that was suitable for use in grid simulation programs and investigated the modeling requirements of a wind turbine in power system studies. It was found that a third-order generator representation, together with two drive train equations and a precalculated shaft torque signal were sufficient to represent a fixed-speed wind turbine for power system simulations. For a variable-speed wind turbine, the control and protection of the converter and generator systems must be included in a model [5,6]. Also importance of calculating initial conditions of the dynamic equipment models for simulation software was emphasized by [7] and [8].

Raiambal and Chellamuthu studied the effects of variation in grid voltage and frequency on the performance of grid connected wind turbines for different wind speeds. A fixed speed wind turbine equipped with a squirrel cage induction generator model and other system components like transformers and transmission lines were presented in MATLAB/Simulink. Based on the simulation results, the best location for the compensating capacitor was suggested [9].

Akhmatov described the considerations and the results of the investigation on short-term voltage stability carried out on a large wind power network model. In the investigation, a distinction was made between large wind farms connected to the transmission network which must ride through three-phased as well as unbalanced short-circuit faults and local wind turbines connected to the distribution networks which could disconnect in case of a grid fault. The large power grid model was implemented in the PSS/E and as a result; access to the strong power grid stated very favorable for the connection of the large offshore wind farms to reduce the demands on the control applied to the grid as well as to the wind turbines [10].

Bleijs analyzed the difference in dynamic behaviour of wind turbines using synchronous and induction generators, connected to different size of networks. Frequency domain analysis of models had been used to quantify the effect of system parameters, such as enhanced drive train damping, diesel governor action and generator slip, on dynamic interaction. The dynamic behaviour was analyzed using standard routines available in MATLAB [11].

Zhou et al. analyzed the detailed WECS model and the impact of different parameters and control system to the voltage stability by simulation in the Electromagnetic Transients Program (EMTP). Analyzed parameters of the system were the short circuit capacity at the PCC, the ratio X/R of the transmission line impedance, the use of static synchronous compensator (STATCOM) for power factor control and rotor speed feedback system [12].

Anandavel et.al. used the mathematical model of the WECS developed in MATLAB to design a neuro controller for power optimization. For a given rated grid voltage and for different wind velocities, as the variation in the duty ratio to capture maximum power from the wind was non-linear, a neural based controller was designed for automatic variation of duty ratio of the DC/DC converter [13].

Slootweg and Kling studied the effects of wind power on the main types of power system oscillations, namely oscillations of a group of generators against a strong system and intra- and inter-area oscillations. The test system was investigated by gradually replacing the power generated by the synchronous generators in the system by power from either constant or variable speed wind turbines, while observing the movement of the eigenvalues through the complex plane. PSS/E was used to calculate the eigenvalues of the investigated scenarios and it was shown that constant speed wind turbines damp power system oscillations more than variable speed turbines [14].

Alanen et.al. studied the effects of variable speed wind power system with dual energy storage, on a typical distribution network by applying the transient simulation software PSCAD/EMTDC. PSCAD/EMTDC enabled a detailed modeling of the inverters involved considering also their switching patterns, which affected on the harmonics generated by the plant. For the wind power plant four different configurations were compared: Fixed speed system, asynchronous generator; Variable speed system, full-scale inverter; Variable speed system, full-scale inverter, dual energy storage system included; Variable speed system, full-scale inverter, dual energy storage system with power quality conditioner (active filter) included [15].

Chen et.al. discussed the voltage variation and flicker emission of grid connected wind turbines with DFIGs. The simulation model of the wind turbine was developed in PSCAD/EMTDC and a method to compensate flicker by using a voltage source converter based STATCOM was presented. The results showed that the STATCOM was an effective means to improve system voltage quality [16].

Muyeen et al. examined the effects of drive train parameters, such as inertia constant, spring constant and damping constant on transient stability analysis using the six-mass, three-mass and two-mass drive train models. Also different types of symmetrical and asymmetrical faults at different wind generator power levels were considered in the simulation analyses with and without considering damping constants in six-mass, three-mass and two-mass shaft models by using PSCAD/EMTDC [17]. Muyeen et.al. discussed the energy capacitor system, composed of power electronic devices and electric double layer capacitor, to enhance the low voltage ride through capability of fixed speed wind turbine generator system during network disturbance. A real grid code defined in the power system was considered and it was concluded that energy capacitor system could significantly enhance the LVRT capability of grid connected WTGS during network disturbance, where simulations had been carried out by using PSCAD/EMTDC [18].

Sharma et.al. performed simulations of a typical wind-diesel hybrid system dynamic model in MATLAB/Simulink . The wind diesel hybrid system transient behaviour was investigated as it undergone various disturbances such as random wind speed, change in load, reactive generation limit, as had the effect of changes in X/R ratios and load on system voltage [19].

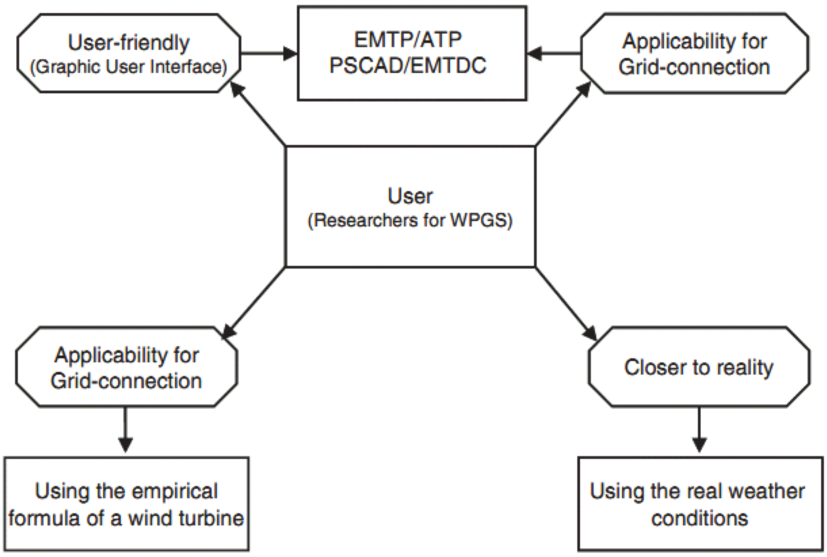

Figure-1 Conceptual diagram of the real weather –Wind Power Generation System(RW-WPGS)[20]

Han et.al. studied modeling of wind turbine system with the real weather conditions introduced by the interface method of a non-linear external parameter of the PSCAD/EMTDC. Three different cases; long term and short term were examined. The efficiency of wind power generator, power converter and flow of energy were analyzed by wind speed of the long-term simulation. The generator output power and current supplied into utility were obtained through the short-term simulation. Conceptual diagram of the real weather –Wind Power Generation System is given in Fig.-1[20].

Arifujjaman presented mathematical modeling and control strategy for the grid connected Permanent Magnet Generator based small wind turbine systems. A novel maximum power flow controller was designed to ensure the sinusoidal current and maximum power output from the inverter to the grid. The results of the MATLAB simulation were shown to prove the concept and to verify the effectiveness of the control strategy [21].

3.1 Aggregated Modeling of Wind Farms

Slootweg & Kling discussed the development and specification of aggregated wind farm models. It was stated that the structure of an aggregated wind farm model should be such, that maximum user friendliness was achieved while keeping the results as close to reality as possible. Structure of aggregated model of Wind Park with constant speed wind turbines and with variable speed wind turbines are given in Fig.-2 and Fig.-3, respectively [3].

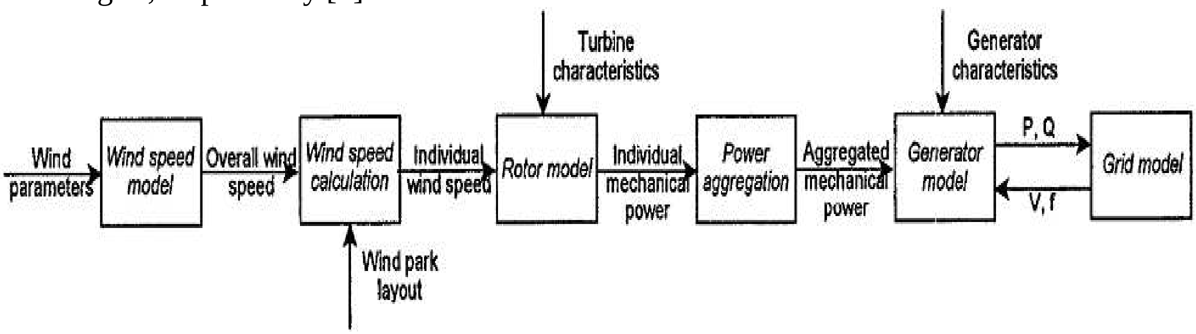

Figure-2 Structure of aggregated model of wind park with constant speed wind turbines [3].

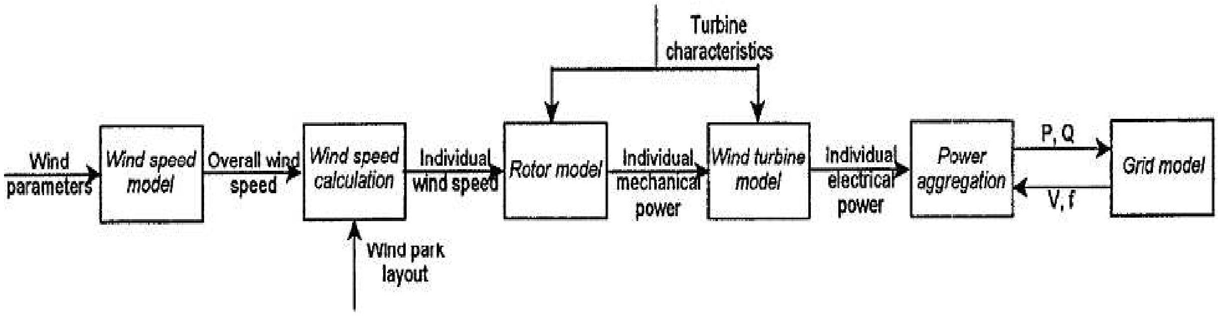

Figure-3 Structure of aggregated model of wind park with variable speed wind turbines [3].

Andersson et.al. reported the studies about possible connection of the 640-MW off-shore wind farm to the 130kV subtransmission system and gave brief description of the wind farm modeling. The wind farm had to be represented in PSS/E, since this tool was used by the grid owner for this kind of studies. Three types of variable-speed wind turbines were considered. The turbines and one-fourth of the wind park were modeled with details in the simulation package PSCAD/EMTDC and subjected to voltage sags. Each cluster of wind turbines in the park was aggregated to one unit. All clusters were then connected to the off-shore collection transformer and connected to the grid via a cable. The results from these simulations were then compared to a simplified model of the wind park developed for PSS/E [22]. Larsson et.al. described the development of a dynamic model of the same wind farm requested by the grid owner in order to receive permission to connect the wind farm to the grid and used the same simulation programs for this purpose [23].

Shafiu et. al. compared the behaviors of aggregated models of a large scale wind farm against the totally individual turbine models in simulation program IPSA+. Wind farm models using squirel cage induction generators and wind farm models using doubly-fed induction generators(DFIG) were implemented in simulation program separately and a transient fault was applied for each one. Comparisons of results were given and differences were highlighted [24].

Akhmatov and Knudsen stated that the aggregate wind farm model could be reduced to one machine equivalent or multi-machine equivalent and presented simulations results of three different model; aggregate model, multi-machine equivalent model and one machine equivalent model. The windmill model was implemented in PSS/E to represent arbitrary number of grid connectedwind turbines within power grids of arbitrary configurations. The fact that the wind farm could not always be represented by the one machine equivalent was explained by the presence of soft coupling of the shaft systems in the wind turbine constructions [25].

Fernandez et.al. proposed a new equivalent model of DFIG wind farms by aggregating all the wind turbines of a wind farm into one single equivalent wind turbine to represent the whole wind farm at PCC to grid, even though the wind turbines operate with different incoming winds. The equivalent model of DFIG wind farm proposed had been verified by comparing the steady-state and dynamic responses of equivalent and complete wind farm models. These wind farm models had been implemented and simulated by using MATLAB/Simulink [26].

Rauma et.al studied the resonances in an aggregated model of a wind power plant with a relatively new method called harmonic resonance mode analysis or simply modal analysis. The results given by this method were validated using the frequency scan (also called the impedance scan). MATLAB was used to carry out the modal analyses and PSCAD/EMTDC to perform the frequency scans [27].

3.2 Verification with Measurement Results

Soerensen et.al. implemented a previously developed model of a large wind farm to the software program PARKWIND for analyzing the power fluctuations from large wind farms. The measurements from the two large offshore wind farms were used to assess the state of the art of that model and to propose improvements of the model. Also two types of model structures were discussed; a diversified model and an aggregated model [28].

Hansen et.al. implemented six 2 MW wind turbine models in DIgSILENT/Power Factory simulation program, to simulate the behaviour of the wind farm during normal operation of wind farm and the ability of the model to predict power quality was investigated. The comparison of the computed power quality characteristics from simulations with measured power quality characteristics, determined by the same computation methods was given and the validation of the model was based on comparisons of the simulations with the measurements for a wind turbine [29]. Hansen et.al. considered the initialization strategy of a dynamic wind turbine model connected to a grid model with the help of models in the same simulation program [8].

Perdana et.al. presented a model of a single wind turbine and an aggregate model of wind farm and the models were validated against field measurement data. The simulations of wind turbines were carried out using PSCAD/EMTDC and MATLAB/Simulink with SimPowerSystem Toolbox. It was proved that the use of an aggregate model of a wind farm with a fifth-order model of the generator in combination with a two-mass model of the drive train was sufficiently accurate for power system dynamics study of a small wind farm consisting of fixed-speed wind turbines [30].

Saniter et.al. presented and compared simulation results using MATLAB/Simulink and measurements of a test bench that had been described for grid-code simulations of multi-MW wind turbines. Topologies of the test bench and control strategy were given. The test bench allowed realistic grid simulations and it was shown that symmetric as well as asymmetric voltage faults cuold be realised with this test bench [31].

Martins et.al. validated a fixed speed, stall regulated 180kW wind turbine model using a recorded case obtained in a wind turbine through a voltage dip. Two different transient stability simulation programs had been used to simulate the recorded case: PSS/E, by Siemens PTI and Power Factory, by DIgSILENT [32].

3.3 Verification with Other Simulation Platforms

Iov et.al. investigated the ability of four different simulation tools; MATLAB, SABER, DIgSILENT/Power Factory and HAWC in a simulation platform. New models and new control algorithms for wind turbines applications had been developed and tested in the considered tools. The developed models and control algorithms were proven to be used in the necessary preliminary studies before connecting wind farms to the power system. Modeling aspects and levels in a WECS is given in Fig.-4 [33].

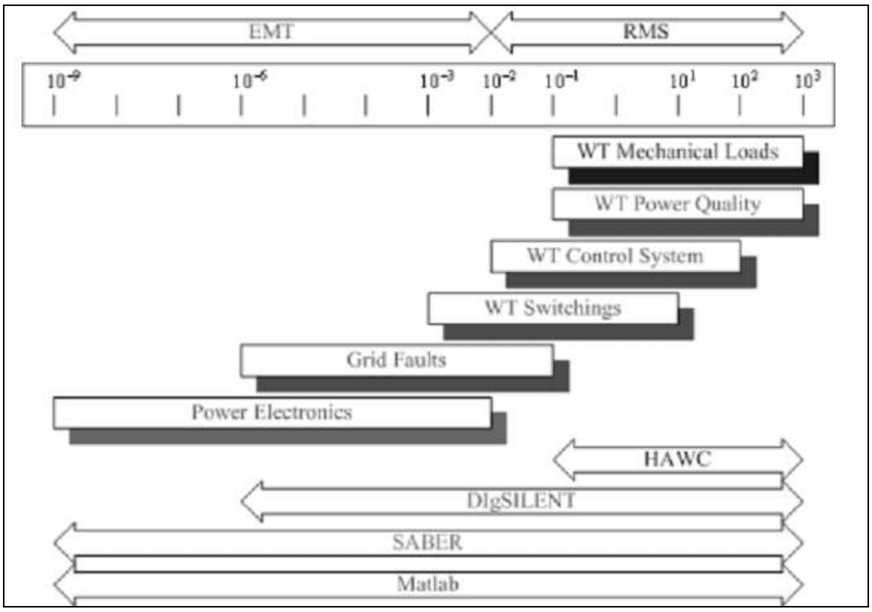

Figure-4 Modeling aspects and levels in a WECS [33].

Petersson et al. presented simulations and experimental verification of the dynamic response to voltage sags of a DFIG wind turbine. Simulations were carried out using a full-order model and with a reduced-order model. Also comparative information was given about the particular properties and required simulation time steps of PSCAD/EMTDC, Simpow and PSS/E [34].

Kazachkov et al. discussed the most significant characteristics and specifics of wind farms that were being developed for the PSS/E. Model validation was addressed by comparison of the response of these models to the response of more detailed, higher-bandwidth models created in a parallel effort for use with the PSCAD/EMTDC program. Also IPLAN program, which was a general-purpose computer language that functioned inside the load flow package and had the ability to access load flow data, was used for the automation of data entry process for both, detailed model and lumped model [35].

Lei et.al. developed a simple DFIG wind turbine model in which the power converter was simulated as a controlled voltage source, regulating the rotor current to meet the command of real and reactive power production. The proposed model had the form of traditional generator model ready to integrate into the power system simulation tool such as PSS/E. An existing grid including wind farm was simulated using the proposed model and the model performance was also compared with the detailed model developed by DIgSILENT/Power Factory [36].

Li et.al. designed a grid frequency controller; an offshore wind farm using DFIGs with line-commutated converters high voltage direct current link connection. The mathematical analysis and control design of offshore wind farm were verified through both MATLAB and PSCAD/EMTDC simulations. The controlled “STATCOM-less” system behaviour under both normal and supply-loss fault conditions had been verified [37].

3.4 Studies with Other Simulation Platforms

Different simulation programs are being used for analyzing the mutual interaction between electric power system and wind farms. PSCAD/EMTDC, MATLAB/Simulink, DIgSILENT/Power Factory, and PSS/E can be named as the most common simulation programs for these analyses.

Haghifam and Omidvar offered a new probability model of power output of wind farm. The simulation program MECORE was used for computation. It was shown in results that the presence of wind power plant in power network had remarkable effects on reliability indices [38].

Efthymiadis et. al. from IPSA Power Engineering presented the load flow analysis, fault level calculation results, controller modeling and dynamic simulations of power system including different wind turbines simulated in IPSA simulation program [39].

Ha and Saha investigated the possibility of integrating the full power of two large wind farms into a subtransmission network, as well as their impacts on the network losses and voltage stability by using NEPLAN, a multi-functional package that supported different types of analysis [40].

Mohammed and Nwankpa simulated the 4-bus power system including a WECS using PowerWorld Simulator and investigated the security and stability of a WECS on an electrical utility to quantify the limits of such a system's operation [41].

Dysko et.al. investigated the effectiveness of Loss of Mains(LOM) protection for future power systems with large portions of embedded generation with respect to the criteria of sensitivity and stability. The performance of actual LOM devices was systematically tested with 16 scenarios; using the ATP transient simulator for SG based scenarios and the RSCAD real-time simulator for DFIG based, respectively [42].

Paap et.al. investigated the influence of voltage sags on the stability of distribution networks with wind generation. The calculation of the network's responses on voltage sags was performed with the software program SIMUNET. From the simulations it followed that stable operation was possible for networks, where the generated power was equal or greater than the local demand [43].

Varma and Auddy presented a study of the oscillations that migth be caused due to interaction between self excited induction generator based wind farm and the series compensated network. Modeling of the system had been performed using different commercial grade software. The steady state modeling of the system for load-flow studies had been performed with PSAT of DSA Power Tools. The steady state power flow results had been used to initialize all the dynamic devices in the nonlinear time domain simulations performed with PSCAD/EMTDC [44].

Norheim et.al. presented a method for assessment of what the impact of increased wind power into an area would have on possible congestion in the grid, and this way enabled decision makers to make sound judgments on how much wind power integration that could be integrated. The duration curves were calculated with the combined power flow and market simulation tool EPF, Energy and Power Flow model. Based on hourly measured wind over one year at a location representing a planned wind farm in the area feeding wind power into the system, a wind power production profile was made [45].

Muljadi et.al. described an analytical approach that could be used to derive the equivalent representation of a wind power plant collector system in particular. To independently verify the calculations, two different concepts were used. The first concept was based on circuit analysis, and the second one was based on load flow analysis. Although the Positive Sequence Load Flow program from General Electric was used for the process, it was stated that other programs, such as PSS/E from Siemens Power Technologies Inc., could also be used [46].

Johnsen and Eliasson presented an aggregate wind farm model for use in real-time power system studies. The model was developed in Matlab/Simulink to operate with the ARISTO-Real Time Simulator System, which had been used for operator training at Swedish National Grid. An entire wind farm was represented with a single wind turbine and developed on a synchronized real-time platform, which enables synchronization of MATLAB and ARISTO [47].

Muljadi and McKenna analyzed a typical wind-diesel hybrid power system for power quality issues using a package program, developed at the National Renewable Energy Laboratory and described the operating characteristics of the components as they relate to power quality in the power network [48].

Muljadi et.al. used PSS/E and Visual Simulation (Vissim) from Visual Solution Inc. to describe various aspects of power quality within a grid connected wind power plant. The sources of disturbances that affect the power quality, the voltage and frequency variations, the voltage and current distortions created by harmonics and self-excitation problem were discussed [49].

BiHui et.al. constructed an automatic generation control simulation model of wind farms with the Full Dynamic Simulation program which had been developed by China electric power research institute. The model controled the conventional units output to verify the effect and influence of automatic generation control in inhibiting the wind power fluctuations. The simulation results showed that, in the normal operation conditions, AGC could effectively reduce the frequency fluctuation brought by wind power integration [50].

5. CONCLUSIONS

This paper has briefly described fifty selected studies about modeling of wind farms for power system simulations. All the WECS concepts had been analyzed due to the power system operational aspects by different researchers. The fundamental parts of these analyses were the simulation programs and the power system models including wind farms. And also verifications of models with site measurement results in existing grid-connected wind farms were usually included in these studies.

Computer simulations require a very responsible approach. The quality of a computer simulation depends on the quality of the built-in models and of the applied data. The results of the computer simulations can be insufficient and unreliable unless the model and data quality are sufficiently high for the problem in question.

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