Wind Power Plant Modeling for the Conditions of Grid-Connected Mode: Modeling

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Abstract— **The load demand to the power grid, as well as the interest in clean and low-cost energy resources, lead to the high integration of wind power plants into the power system grid. There are grid code standards that are set for the design and integration of these wind power plants. These codes often look at the design operation of the wind power plant in islanded mode, where possible analysis of the most sensitive power system quantities such as voltage, frequency, reactive power, etcetera is done. Therefore, attention needs to be paid to the application of these codes to keep the design and integration of wind power plants well standardized as much as possible. The purpose of this research is to review and discuss the literature and theory about the design of the wind turbine generators, model the wind power plant, and integrate it into the power system grid while adhering to the grid code requirements.**

Keywords— Integration, Point of Common Coupling (PoCC), Renewable Power Plant (RPP), South African Renewable Grid Code Standards (SAREGCS), Wind Power Plant (WPP), Wind Turbine, Wind Turbine Generator Unit (WTGU), Wind Turbine Power Coefficient (Cp).

I. INTRODUCTION

Adherence to grid codes ensures the proper design, installation, and operation of wind power plants (WPPs) while guaranteeing an effective contribution to the grid through the fulfillment of the load demand requirements.

Various studies have been conducted relevant to the integration of WPPs into the grid. However, only a few consider the operation of WPP on standalone mode, which guarantees the appropriate grid compliance test before integration.

Paper 1 discussed the grid code requirements and reviews the design of the wind turbine generator. This paper deals with the modeling of a WPP and the grid compliance test.

II. THE WIND POWER PLANT MODEL

The wind power plant considered for this study is modeled using the existing parameters from Vestas. The turbine is driving a squirrel-cage induction generator model whose parameters are adopted from published and recognized literature. These parameters are listed in Table I [1] and Table II [2].

TABLE I. SQUIRREL-CAGE INDUCTION GENERATOR PARAMETERS

Parameter	Values	Per-unit values
Rated output power	4.0 MW	-
Rated mechanical power	4.0606 MW	
Rated apparent power	4.842 MVA	
Rated line-to-line voltage	4000 V (rms)	
Rated phase voltage = Base voltage	2309.4 V (rms)	
Rated stator current = Base current	698.88 A (rms)	
Rated power factor	0.8261	
Rated rotor speed	1 510.5 RPM	
Rated mechanical torque	25.671 kN.m	
Rated stator flux linkage	7.3917 Wb (rms)	
Rated rotor flux linkage	6.7114 Wb (rms)	
Stator winding resistance	22.104 mΩ	0.0067
Rotor winding resistance	23.1515 mΩ	0.0069
Stator leakage inductance	1.698 mH	
Stator leakage reactance	j0.53344 Ω	j0.1615
Rotor leakage inductance	1.698 mH	
Rotor leakage reactance	j0.53344 Ω	j0.1615
Magnetizing inductance	33.597 mH	
Magnetizing reactance	j10.5548 Ω	j3.1946
Base flux linkage	7.3511 Wb (rms)	
Base impedance	3.3044 Ω	
Base inductance	10.518 mH	
Base capacitance	963.29 u.F	

TABLE II. VESTAS V117-4.2 MW WIND TURBINE AND ROTOR DATA

Parameter	Values
Rotor diameter (D_R)	117 m
Swept area (A_S)	10.751 m^2
Minimum turbine angular rotor, ω_{TRMin}	2.1 RPM = 0.22 rad/sec

Parameter	Values
Nominal turbine angular rotor ω_{TRN}	9.9 RPM = 1.035 rad/sec
Maximum turbine angular rotor ω_{TRMax}	17.7 RPM = 1.85 rad/sec

III. Wind Power Plant Modeling

This section covers the modeling of the wind turbine, squirrel-cage induction generator, wind turbine generator substation unit (WTGSU) transformer, transmission line modeling, the wind power plant reactive power compensator respectively.

A. Wind turbine model

The wind turbine generator requires a mechanical prime-mover to produce electrical power. The Vestas V117-4.2 MW wind turbine is selected for this purpose and is modeled on the RSCAD as shown in Fig. 1.
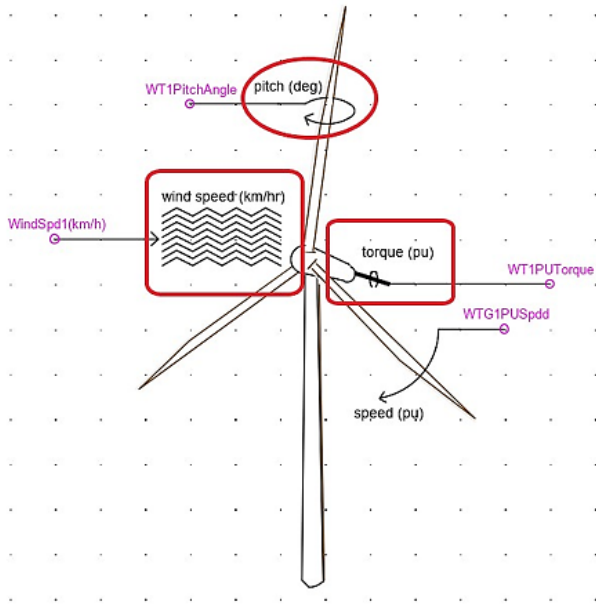

Fig. 1. RSCAD wind turbine model

It has three input signals written pitch (deg), wind speed (km/hr), and speed (pu) shown in the red zones. To get this wind turbine model working, parameters need to be set and the mapping of control and calculation logics for these input signals is required. In this part, the setting of wind turbine generator parameters, modeling of control, and calculation logic are done. Once these control and calculation logics are modeled, an output signal with the name torque (pu) is then coupled to a generator for the conversion of mechanical power to electrical power.

1) Wind turbine modeling

The three inputs and one output, *pitch (deg)*, wind speed *(km/hr)* and *speed (pu)*, and *torque (pu)* were defined as shown in Fig. 1. The signals named *WindSpd1(km/h)* and *WT1PitchAngle* are input signals from the wind speed and pitch angle adjustment component. *WTG1PUSpdd* is the feedback per unit speed signal from the driven generator. *WT1PUTorque* is the output per unit torque. This signal drives the generator coupled to the wind turbine.

Wind turbines convert about 40% up to 48% of the power produced by the moving wind and transfer it to the generator rotor through the torque mechanism, wherein the later stage is converted to electrical power.

The percentage values stated above represent the efficiency of the wind turbine, which is referred to as the turbine's power coefficient (C_p).

Various equations exist for this parameter. However, the wind power plant model for this study is based on the equation

$$C_p = k_1(\lambda + k_2\beta^2 + k_3)e^{k_4\lambda} \qquad (1)$$

where β and λ are the pitch angle adjustment of the wind turbine blades and the tip speed ratio of the wind turbine.

The tip speed ratio (λ) is given by the following expression

$$\lambda = \frac{v_W}{\omega_{TR}} \qquad (2)$$

In the expression, v_W and ω_{TR} are the velocity of wind in meters per second (m/s) and rotational velocity of the turbine rotor in radians per second (rad/sec) respectively.

The constants in expression (1) have the values, $k_1 = -0.5$, $k_2 = -0.022$, $k_3 = -5.6$ and $k_4 = -0.17$. Fig. 2 shows the C_p setting values for the constants, k_1, k_2, k_3 and k_4 considered for all the wind turbine models used in this paper.

Fig. 2. Power coefficient (Cp) parameter settings of the wind turbine

The literature exists with different equations for the design of wind turbine efficiency *(Cp)*. However, for this paper, we considered Equation (1) due to some difficulties we would experience in RSCAD to define several constants specified for some of the equations.

The wind turbine operating characteristic exists, formed by plotting the corresponding C_p points versus the wind speed. These curves also depend on the value of the pitch angle. To plot the C_p versus *Wind Speed (v_w)* characteristic curve, the study makes use of at least five-pitch angle adjustments, namely. $\beta1 = 0°$, $\beta2 = 5°$, $\beta3 = 10°$, $\beta4 = 20°$ and $\beta5 = 32°$. These values are selected because they are common in the literature, and they justify the relationship between the two variables, C_p and v_w.

2) Gearbox modeling

The wind turbine generator model in this study has the turbine rotor rotational speed of 9.9 RPM at nominal, and the induction generator shaft requires thousands of RPMs to produce a reasonable amount of power.

A gearbox ratio was calculated by using the nominal values of the wind turbine and the generator rotor speed. At a

nominal wind speed of 14 m/s, the wind turbine hub rotational speed is 9.9 RPM while the rated rotor speed of the induction generator is 1510.5 RPM.

The generator's rated output power is produced at the rated speed.

The gearbox ratio is determined from the expression

$$\omega_{GR} = G\omega_{TR} \tag{3}$$

In the expression, G is the gearbox ratio, ω_{GR} and ω_{TR} are the rated angular rotor speed of the generator's rotor and the wind turbine.

To calculate the value of the gearbox ratio, G was made the subject of the above expression as follows

$$G = \frac{\omega_{GR}}{\omega_{TR}} \tag{4}$$

The nominal speed values for both the wind turbine hub and the induction generator are substituted as follow

$$G = \frac{1510.5\ rpm}{9.9\ rpm}$$

$$G = \frac{50.35\pi\ \frac{rad}{s}}{1.036705\frac{rad}{sec}}$$

$$G = 152.5757576$$

We also used another method to calculate the gearbox ratio by looking at the amount of torque required by the generator, in comparison with the one produced by the turbine. The mechanical torque expression of the wind turbine is written as

$$T_T = \frac{P_T}{\omega_{TR}} \tag{5}$$

In the expression, T_T and P_T are the mechanical torque in Newton-meters (N.m), and power in Megawatts (MW), produced by the wind turbine.

The amount of torque required by the generator to produce the nominal power of 4 MW is 25.671 kN.m and the torque produced by the wind turbine is calculated as follows.

$$T_T = \frac{4\ MW}{1.036705\frac{rad}{sec}}$$

$$T_T = 3.858378\ MN.m$$

The mechanical torque transfer calculation was done through the gearbox of the wind turbine using the principle defined by the expression

$$T_G = \frac{T_T}{G} \tag{6}$$

In the above expression, T_G is the generator torque. Also, G is made the subject of the formula and the following expression is obtained

$$G = \frac{T_T}{T_G} \tag{7}$$

The values, 3.858378 MN.m, and 25.671 kN.m were then substituted in the variables, T_T and T_G as follows

$$G = \frac{3.858378\ MN.m}{25.671\ kN.m}$$

$$G = 152.5757576$$

Fig. 3 shows the gearbox ratio and the turbine rotor radius parameter settings.

Fig. 3.   Wind turbine rotor radius and gearbox ratio parameter settings

In addition to the wind turbine gearbox parameter settings and the rotor radius, the rated MVA, rated frequency, as well as rated RPM of the generator coupled to the wind turbine are set as shown in Fig. 4.

Fig. 4.   Wind turbine generator rated apparent power (MVA), frequency, and rotor speed (RPM)

The standard operating temperature range for the wind turbine considered for this paper is $-20\ ^\circ$C to $45\ ^\circ$C. A decision is made on the default temperature value of $25\ ^\circ$C, where the wind turbine is assumed to be producing the nominal power of 4/4.2 MW. The default setting value is shown in Fig. 5, with that of the default barometric pressure and the percentage humidity.

Fig. 5.   Setting values for the default air temperature, barometric pressure, and relativity

Certain quantities are monitored and their availability on runtime depends on the settings done during the modeling. The part below presents the modeling for wind turbine control, monitoring and calculation logic.

3) Modeling of wind turbine control, monitoring, and calculation logic

The wind turbine model produces the output per unit torque or high-speed rotation based on the two principal input signals, the pitch angle control adjustment, and wind speed. The control logic for these inputs is shown in Fig. 6.

The wind speed range specified in the given wind turbine specifications is in meters per second (m/s) and the wind speed input signal to the turbine model provided is required in kilometers per hour (km/h). It is more precise to monitor and tune the wind speed in meters per second. A logic is

developed, and its adjustments are in m/s while the output is in units (km/h) required by the wind turbine.

The equation is derived for this function and its mathematical expression is

$$x = 3.6(v_W) \qquad (8)$$

In the expression, x represents the wind speed in km/h and v_W is the wind speed in m/s. The component with X is the multiplier, and the component labeled *WindSpd1Adjust* is the slider for tuning the wind speed range.

An output from the slider is labeled *WindSpd1(m/s)* and it multiplies with the constant number 3.6 as shown in Fig. 6. The output labeled *WindSpd1(km/h)* is a signal name that signally connects the output of the logic to the wind speed input on the wind turbine.

Also, in the same figure, Zone 1 shows the dial selector switch for the selection of the angle at which the turbine blades are facing the wind, with its output signal named *WT1PitchAngle*. The logic to perform this calculation is shown in Zone 2 of Fig. 6.
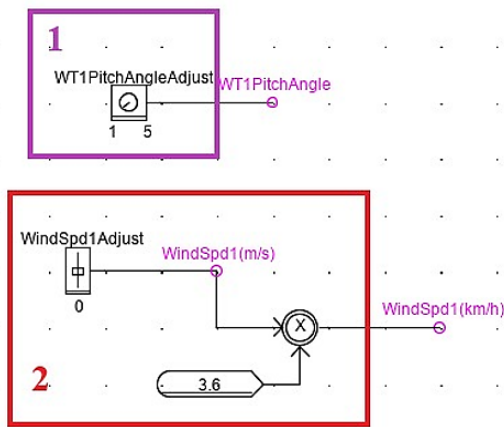

Fig. 6. Wind turbine generator blades pitch angle and wind speed adjustment and calculation logics

Since the wind speed range is specified from 3 m/s up to 25 m/s, the slider is set such that the adjustment is made from 0 m/s up to 50 m/s for evaluation purposes. The input parameter settings for the WindSpd1Adjust slider are shown in Fig. 7 below.

Fig. 7. Wind speed adjustment settings

The pitch angle adjustment of a wind turbine is not as simple as just punching values in degrees (of rotation). Various parameters are put into consideration in modeling a controller for this feature. Because of the time that would be spent in designing a controller for this purpose, as well as the theory to be undergone for more understanding about controllers, the study uses a dial selector switch for this

feature, whose application does not affect the emphasis of the study.

Fig. 8. Wind turbine blade pitch angle adjustment slider settings

The dial selector switch configuration settings are shown in Fig. 8. In the figure, it is shown that the number of positions is set to 5, each position specifying the value of the pitch angle (β). The settings for these positions are shown in Fig. 9.

Fig. 9. Settings for slider pitch angle values in degrees of rotation

The wind speed operating range of the Vestas V117-4.2 MW wind turbine is specified from 3 m/s to 25 m/s. Also, the rotational (angular) speed of the turbine rotor is specified in correspondence to the wind speed range and the data is shown in Table III.

TABLE III.   WIND SPEED AND THE ANGULAR SPEED OF THE WIND TURBINE ROTOR

Wind speed	Wind turbine rotor angular speed (RPM)	Wind turbine rotor angular speed (rad/sec)
3	2.1	0.219911
14	9.9	1.036705
23	-	-
25	17.6	1.843068

Because the tip speed ratio is calculated from a rad/sec value, the turbine rotor speed was converted from RPM to a rad/sec unit and the values are shown in the third column in the table above. Two parameters influence the turbine efficiency (Cp), β and λ. The Cp values are determined for each tip speed ratio with different pitch angle adjustments and the results are shown in Table IV.

TABLE IV.   WIND SPEED AND THE ANGULAR SPEED OF THE WIND TURBINE ROTOR BASED ON THE 32 DEGREES PITCH ANGLE ADJUSTMENT

V_W	Cp	ω_H	λ	β
3	0.405892	0.219911	13	0
14	0.375725	1.036705	13	5
25	0.285222	1.843068	13	10
36	-0.07679	2.666666	13	20
47	-0.82978	3.48	13	32

The value of the tip speed ratio (λ) is constant because the relationship between the increase in wind speed is directly proportional to the increase in the angular speed of the turbine rotor. The turbine coefficient (Cp) versus wind speed curve is plotted for this wind turbine and is shown in Fig. 10. This curve is plotted using different values of β and λ. The graph obtained in the plot shows the maximum value of Cp at $0\,°$ and it follows the same characteristics as the literature.
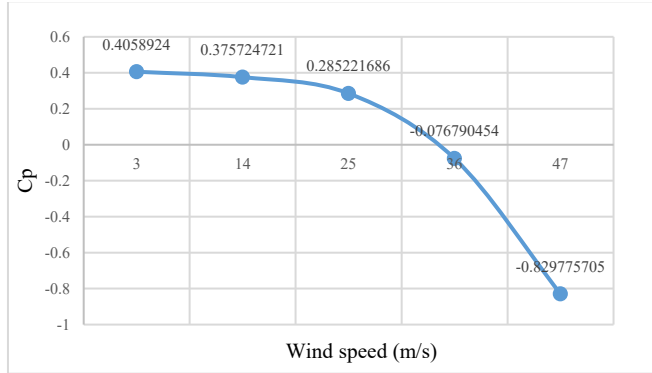

Fig. 10. Turbine power coefficient versus the wind speed at different pitch angle adjustments

The pitch angle controller controls the value of Cp, to produce the rated power at multiple ranges of wind speed. When the wind speed is increasing and the pitch angle is 0.4, the power produced by the wind turbine will be of a huge amount. Tuning the value of Cp to a lesser value will reduce the power output of the wind turbine. Also, when the wind speed is less, the power will be less, therefore tuning of Cp to a higher value increase the power output of the wind turbine.

However, the Cp versus the wind speed characteristic for a wind power plant presented in this paper may not be the same as the one found in the literature. This is due to the absence of the pitch angle controller. Besides, the pitch angle controller does not affect the desired output power from the model.
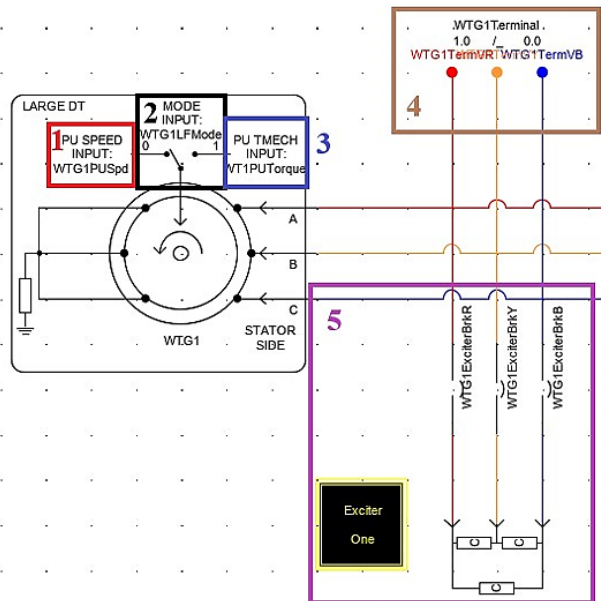
B. Induction generator model

Fig. 11. The squirrel-cage induction generator model with the exciter circuit

The power measured from the output of the wind turbine is the mechanical power and is transferred in the form of a per-unit mechanical torque to the generator it is coupled with. The generator selected for this study is a squirrel-cage induction generator for its simplicity and low-costs. Fig. 11 shows the induction generator model.

The induction generator model in the figure has three input signals written and shown in Zone 1, Zone 2, and Zone 3 as *PU SPEED INPUT*, *MODE INPUT*, and *PU TMECH INPUT*. The two input signals are shown in Zone 1 and Zone 3, one is used, depending on the selected input signal which is controlled by the input signal in Zone 2, which is the MODE input signal.

The mode of operation of the induction generator is discussed in the following parts during the modeling of controls, calculation, and monitoring logic.

The circuit shown in Zone 5 of Fig. 11 is the exciter circuit and is connected to the stator terminals of the induction generator represented by a node in Zone 4. This circuit assists in the building up of the induction generator's stator terminal output voltage.

To ensure the operation of the induction generator model, some parameters must be defined, as well as the mapping of control and calculation logics for these input signals.

1) Squirrel-cage induction generator modeling
One of the most important settings in induction generator modeling is that of defining the motor electrical parameters as shown in Fig. 12.

Fig. 12. Squirrel-cage induction generator model electrical parameter settings

The stator, rotor and core resistance, and reactance parameters of this machine are entered in per-unit values. These values are calculated from the base values specified by the guide for RSCAD induction generator modeling.

The following are base values specified for calculating the per-unit values of the machine:

- Base voltage (V_B): Rated line-to-neutral stator voltage of the generator as the base value for the voltage.

- Power: Rated MVA of the machine is used as the base value for the power.

- Base current (I_B): Rated stator current of the machine is used as the base value for the current

- Base impedance (Z_B): The ratio of the base voltage (V_B) over the base current (I_B) is used as the base value for the base impedance.

Another setting is that of the generator's inertia constant. As specified from its units, MWs/MVA, is calculated from the values provided in the generator specifications and the value is set in the mechanical parameters as shown in Fig. 13 of the induction generator parameter settings.

If_rtds_risc_sld_INDM

ENABLE MONITORING IN RUNTIME	SIGNAL NAMES FOR RUNTIME				
MACHINE SATURATION CURVE BY FACTORS		MONITORING OPTIONS			
MOTOR ELECTRICAL PARAMETERS		MECHANICAL PARAMETERS			
INITIAL CONDITIONS	LOAD FLOW	CONTROLS COMPILER INPUT			
INDUCTION MACHINE CONFIGURATION		PROCESSOR ASSIGNMENT			

Name	Description	Value	Unit	Min	Max
H	Inertia Constant	0.8386204048	MWs/MVA	0.01	
D	Frictional Damping	0.001	pu/pu	0.0	
syndm	Friction is relative to a speed of:	Zero			
telfr	Required Torque (Te) output is Telect + :	Friction			

Update   Cancel   Cancel All

Fig. 13. Squirrel-cage induction generator model mechanical parameter settings

The induction generator produces electric power by converting the mechanical power input to its shaft. The voltage at the generator's stator terminal will never build up even the torque from the prime mover is enough.

For a voltage build-up on the stator terminals of the induction generator, an exciting circuit is required. This circuit produces the voltage from the small amount of current available at the stator terminals during the rotation of the generator's rotor.

2) Design and modeling of squirrel-cage induction generator excitation circuit

The squirrel-cage induction generator's rated values were used for this calculation. The apparent power (S) was calculated from the rated current and voltage of the induction generator using the equation

$$S = \sqrt{3} IV \tag{9}$$

$$S = \sqrt{3}\,(0.69888A)(4\,kV)$$

$$S = 4.84198\,MVA$$

Induction machines draw a lagging current from the circuit, and their power factor is usually assumed to be 0.8 lagging. Therefore, the active power was calculated as

$$P = 4.84198\,MVA\,(0.8261)$$

$$P = 3.999999\,MW$$

The total reactive power required from the excitation circuit was calculated using the values of the active and apparent power determined above. The equation

$$Q_T = \sqrt{S^2 - P^2} \tag{10}$$

is used.

In the equation, Q_T is the total reactive power of the excitation circuit and is calculated as

$$Q_T = \sqrt{(4.84198\,MVA)^2 - (3.99999\,MW)^2}$$

$$Q_T = 2.72853\,MVAr$$

The value calculated here is the minimum reactive power required to excite the induction machine to produce a voltage at the stator terminals. For low-cost, the combination of the capacitors to produce Q_T is usually connected in delta connection. In this connection, the capacitive reactance is three times less than the total reactive power of the circuit. Therefore, the value of 0.909510 MVAr is determined for the excitation circuit model presented in this paper.

From this, we calculated the current that will flow through each capacitor using the equation

$$I_Q = \frac{Q_P}{V_{Phase}} \tag{11}$$

In the expression, I_Q, Q_P and V_{Phase} are the current flow in the reactive component, the per-phase reactive power of the excitation circuit, and the per-phase voltage. The voltage is equal to the line-to-line voltage because of the connection method of the reactive component. The reactive current is then calculated as

$$I_Q = \frac{0.909510\,MVAr}{4\,kV}$$

$$I_Q = 0.22738\,kA$$

Also, the capacitive reactance of the per-phase capacitor is determined using the equation

$$X_C = \frac{V}{I_Q} \tag{12}$$

In the equation, X_C is the capacitive reactance for each capacitor and is calculated as

$$X_C = \frac{4\,kV}{0.22738\,kA}$$

$$X_C = 17.591697\,\Omega$$

The setting parameters of the reactive power compensator device used in RSCAD are entered in per-phase micro-Farads. The per-phase micro-Farads value for this circuit is determined using the expression

$$C_P = \frac{1}{2\pi f X_C} \tag{13}$$

In the expression, Cp is the amount of per-phase capacitance required for each capacitor to generate the minimum amount of the per-phase reactive power, f is the rated frequency of the generator. The calculation is done as

$$C_P = \frac{1}{2\pi(50)(17.591697)}$$

$$C_P = 180.94325\,uF$$

C_P is the amount of the per-phase capacitance to be connected to the induction generator stator terminals its excitation. Fig. 14 shows the parameter settings entered for the excitation circuit used for an induction generator.

If_rtds_sharc_sld_SHUNTCAP

CONFIGURATION	CURRENT MONITORING NAMES				

Name	Description	Value	Unit	Min	Max
CuF	Shunt Capacitance per phase	180.94325	uF	1E-9	1E6
type	Connection type	Delta		0	1
NR	Include Neutral Connection Point?	No		0	1
Imon	Monitor Branch Current in RunTime?	Yes			

Update   Cancel   Cancel All

Fig. 14. Squirrel-cage induction generator model mechanical parameter settings

In a wind power plant, induction generators are connected in parallel, and the excitation capacitor banks connected to each terminal of a generator make parallel circuits. The capacitor banks, when connected in parallel increase the capacitance in the system. That being said, the value of the capacitance calculated above may vary, depending on the number of wind turbine generators connected to complete the wind power plant.

Therefore, the value of the capacitance for the excitation circuit depends on the connected number of wind turbine generator units, and in this paper, we present no fixed value of the capacitance.

3) Modeling of squirrel-cage induction generator control, monitoring, and calculation logic

A relationship between wind speed and the turbine rotor speed. The rotor speed increases as the wind speed increases. Because of this relationship and the per-unit speed control input to the driven generator, a logic is designed, that calculates the per-unit speed from the speed of the wind.

The nominal speed of the wind is 14 m/s, and the wind turbine is expected to be producing the nominal power of 4/4.2 MW at this speed. At 14 m/s of wind speed, the speed input to the generator is expected to be at 1 per unit. The logic was designed as shown in Fig. 15.
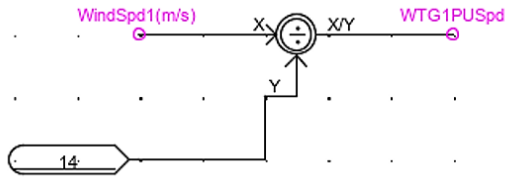

Fig. 15. The logic for wind turbine generator per-unit speed control

In the figure above, constant 14 is the rated wind speed in meters per second (m/s) and is used as the base value for obtaining the per-unit output signal. The designed logic makes use of the calculated per-unit speed of the wind and applies it to the generator.

The component with a division sign produces the output signal assigned *WTG1PUSpd*. The signal *WindSpeed1(m/s)* is the output from the wind input speed adjusting slider for the wind turbine. The *WTG1PUSpd* signal is connected to the generator as part of the control signals.

Three signal names were also defined for the control of the induction generator as shown in Fig. 16.

Fig. 16. Control's compiler settings for the induction generator model

The signal named *WTG1LFMode* controls the mode of operation of the induction generator. When the Lock/Free Switch (*WTG1LFSW*) is put on *Free Mode* (OFF state), the generator operates using the input signal *WTG1PUTorque* and operates through the input signal *WTG1PUSpd* when the switch is positioned the other way.

Another mapping of signals exists between the wind turbine and the induction generator, namely, the per-unit feedback speed from the induction generator to the wind turbine. Input to the wind turbine this signal is *WTG1PUSpdd*. This signal is made available by setting parameters to monitor in the induction generator as shown in Fig. 17.

Fig. 17. Control's compiler settings for induction generator model

Part of the signals monitored in the figure is the stator currents, electrical torque, the rotor speed of the generator, the output electrical real (P), and reactive (Q) power. Setting these quantities makes them available on the run-time simulation cases for monitoring purposes.

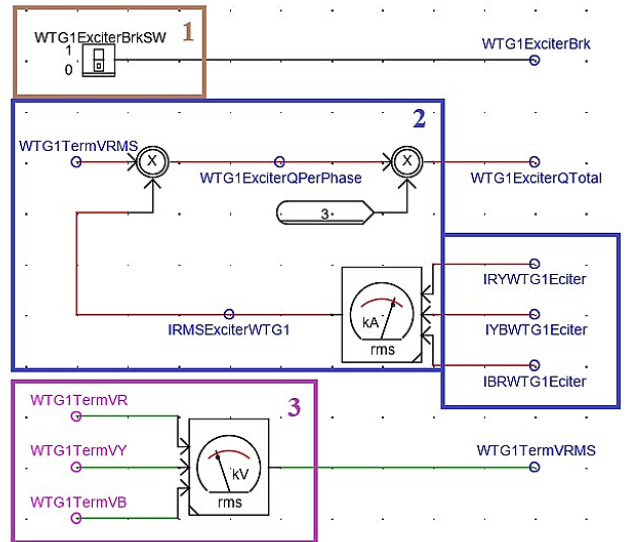Fig. 18. Excitation circuit control, monitoring, and calculation logic

The excitation circuit model for the induction generator model requires control, monitoring, and calculation logic. A logic to perform these functions is shown in Fig. 18. In the figure, Zone 1 shows a switch for controlling the circuit breaker for switching ON/OFF the excitation circuit. Zone 2 shows the logic for calculating and monitoring the reactive

power produced by the excitation circuit. This logic determines the reactive power using the product of the RMS current and voltage seen by the circuit.

Fig. 19. Induction generator exciter phase current signal settings for the calculation and monitoring of reactive power, exciter current, and voltage

The signals named *IRYWTG1Eciter*, *IYBWTG1Eciter*, and *IBRWTG1Eciter* shown in Zone 2 are the phase currents monitored from the exciter circuit. These signals are found in the settings of the capacitor bank model and were set for monitoring as shown in Fig. 19.

C. Wind power plant power transformer modeling

A complete wind power plant consists of power system components such as generator units, step-up transformers to step up the generated low-voltage to a medium voltage connected to the collector circuit, the medium voltage to high-voltage transformers for stepping up the voltage to a transmission level voltage [3].

The transformers of 5 MVA were selected for each wind turbine generator substation unit (WTGSU). Having looked at the WTGSU transformer capacity of 5 MVA, there are six of these transformers and at full load, each would deliver 5 MVA to the collector busbar. From the collector exists a 24 kV to 230 kV step-up transformer required to deliver eighteen times 5 MVA (equals 90 MVA) to the transmission system through the transmission lines. Therefore, a 90 MVA transformer is selected.

With all the major components modeled, each wind turbine generator unit is connected to the collector busbar through WTGSUs (transformers) to complete the collector circuit.

Power generating plants are usually located in remote areas, away from customers. Some literature specifies one of the advantages pertinent to wind power plants is that they provide clean power closer to the load.

However, depending on the mode of operation the wind power plant is operated at, this advantage may not be true for all the wind power plants. Power is generated and transmitted to where it is required. To achieve this, a transmission line must be modeled for a wind power plant, to make sure that the power reaches the customers even in the remote area. In the case of the transmission system model used for this study, this makes modeling easier as the RSCAD model uses more than one subsystem. To interconnect two or more power system circuits between subsystems, transmission line models are used. The following part presents the transmission line modeling for the wind power plant.

D. Wind power plant high-voltage transmission line modeling on rscad

RSCAD offers two models of transmission lines, the traveling wave transmission lines and PI section models. Both these models represent transmission lines on the RSCAD. The traveling wave transmission line model is generally preferred

only for line models with a length of 15 km and above. Otherwise, the PI section model is used. There are several advantages and disadvantages to these transmission line models. However, for the aim of interconnecting the two systems in this study, the traveling wave transmission line model becomes the best option because it allows the interconnection of two or more subsystems while guaranteeing accuracy. A 15 km transmission line model is used for this model, interconnecting the two systems, the transmission, and wind power plant system under study.

The parameters used for this transmission line model are obtained from one of the RTDS tutorials, whose data is reliable and does not deviate from the aim of the study. The original line had a length of 100 km and is reduced to 15 km. This is done to reduce power losses while the purpose of a wind power plant model is kept realistic.

The grid code requirements also address the frequency, voltage, and reactive power or power factor at the point of common coupling of the wind power plant. The voltage is specified for continuous operation from 0.9 up to 1.0985 per unit for this category. Also, the power factor must be 0.95 and more at the common point of coupling.

The power generated by the wind power plant understudy the minimum power Category C renewable power plants can generate. Also, the reactive power it generates is of a low quantity, therefore not expected to send it as it is at the receiving end terminal of the transmission system model due to the transmission lines that are rich in the magnetic circuit, which cause a huge absorption of reactive power through the line. For this reason, the same approach of generating and compensating for the reactive power absorbed during the transmission is done at the sending receiving end terminal of the wind power plant transmission line system. Therefore, a wind power plant reactive power-producing device is modeled in the following part.

E. Wind power plant receiving end reactive power compensator device modeling

The load demand of 15 MW is considered in this paper. Therefore, the WPP of at least 15 MW is modeled. Corresponding to the active power, the grid codes specify the power factor at the terminals of the Category C renewable power plants at a value of 0.95. The corresponding reactive power for this amount of active power at a power factor of 0.95 is 4.930261578 MVAr. This is the minimum value of the reactive power compensator device that must be connected at the receiving end terminal of the wind power plant to produce the power factor of 0.95 when the active power produced is 15 MW.

The reactive power compensator device uses capacitor banks. The capacitance of the capacitor bank is calculated using the expression

$$C_P = \frac{I_Q}{2\pi f V_P} \qquad (14)$$

In the above expression, I_Q and V_{Phase} are the current flow in the reactive component and the per-phase voltage, which is equal to the line-to-line voltage because of the connection method of the reactive component.

The value of I_Q can be found by using the expression

$$I_Q = \frac{Q_P}{V_{Phase}} \qquad (15)$$

In the above expression, Q_P is the per-phase reactance of the capacitor bank.

The value of the current is then calculated as

$$I_Q = \frac{1.643420526 \; MVAr}{0.9(230 \; kV)}$$

$$I_Q = 0.07939229594 \; kA$$

Therefore,

$$C_P = \frac{0.07939229594 \; kA}{2\pi(50)(0.9 \; PU)(230 \; kV)}$$

$$C_P = 0.1220838294 \; \mu F$$

Capacitor banks cause a lot of transient currents in the power system, which might affect other power system components. The transients are reduced by sequential switching. In the case of sequential switching, capacitor banks are divided into units and this becomes very effective in reducing the transients.

For the capacitor bank presented above, a decision is taken, that there are fourteen units. Therefore, each unit is fourteen times less than $0.1220838294 \; \mu F$, which then gives $0.00872035286 \; \mu F$ capacitor bank. The settings parameter for each capacitor is shown in Fig. 20.

Fig. 20. WPP terminal reactive power compensator device model settings parameters

Only one unit is shown in this part, though all other units have the same settings menu, with different labeling of signals.

Monitoring is also a requirement for a reactive power compensator. A relationship exists between the current, voltage, and the reactive power produced by the capacitor bank. Using this relationship, the total reactive power contribution can be monitored at the busbar where these capacitor bank units are connected. The logic is shown in Fig. 21.
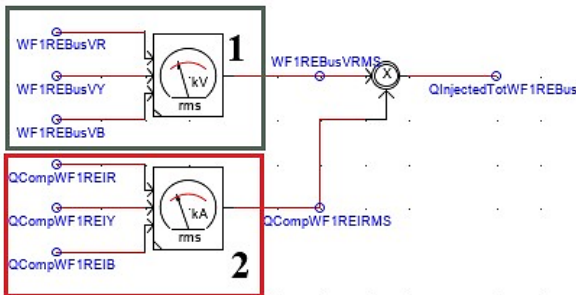

Fig. 21. Monitoring and calculation logic for reactive power injection device using the RMS voltage and current

In the figure, Zone 1 shows the logic to calculate the RMS voltage from the busbar at which the reactive power compensator devices are connected. Also in Zone 2, another

RMS current calculator logic is shown, it monitors the total line current drawn by the active capacitor bank unit. The RMS output from both zones is multiplied and the product gives the total reactive power injected.

The sequence switching of the capacitors for the reactive power compensator device is achieved by the logic shown in Fig. 22. Similar logics exist for the rest of the capacitors.
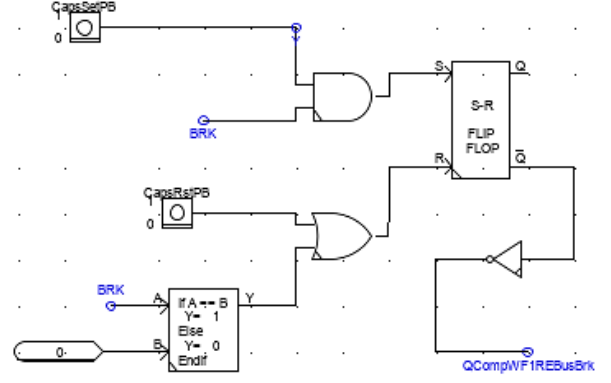

Fig. 22. Monitoring and calculation logic for reactive power injection device switching logic

IV. Wind Power Plant Grid Code Compliance Test

Under this test, the power flow was conducted where the aerodynamic, mechanical, and electrical quantities were monitored. The operating temperature range for this wind turbine is from $-20^o C$ to $45^o C$, the test is done at the temperature of $25^o C$.

TABLE V. Wind Turbine Generator Unit Monitoring At The Steady-State Power Flow

Mechanical quantities		Electrical quantities	
Quantity names	Values	Quantity names	Values
Wind speed	14 m/s	WTGSU primary current	0.01563 kA
Wind power	23.31 MW	WTGSU secondary current	0.00130 kA
Wind turbine Cp	0.1718	WTG electrical torque	0.00986 PU
Wind turbine power	4.003 MW	WTG terminal voltage	1.083 PU
Wind turbine rotor speed	9.9 RPM	WTG exciter reactive power	2.122 MVAr
Wind turbine torque	3.858 MN.m	WTG active power (P) output	0.02404 MW
		WTG reactive power (Q) output	-2.010 MVAr
		WTG reactive power circuit current	0.1633 kA

For as long as the temperature is within the specified operating range, the output power of the turbine may still be tuned to the desired output. Humidity and air pressure also play a role in the value of Cp and are set to 30% and 1415 mbar. The mechanical and electrical quantities were monitored during the steady-state operation of the wind power plant and at least one wind turbine generator unit results are shown in Table V.

The study assumes that all the WTGUs are synchronized, therefore, results are the same for all the units. The wind power plant receiving end terminal is one of the most important points in a wind power plant. This is the point at which the grid code specifications are mostly referred to. Table VI shows the results of the monitored quantities at this point at steady-state power flow.

TABLE VI.   WIND SENDING-END AND RECEIVING-END MONITORED VALUES AT THE STEADY-STATE POWER FLOW

Quantity names	Actual values	Per unit values
Group 1 collector terminal voltage	26.02 kV	1.084 PU
Wind farm sending-end bus voltage	249.9 kV	1.086 PU
Wind farm receiving-end bus voltage	249.9 kV	1.086 PU
Wind farm sending-end frequency	50 Hz	-
Wind farm receiving-end frequency	50 Hz	-

The grid codes specify the continuous operating per-unit voltage level for Category C renewable power plants as 0.9 (minimum) to 1.0985 (maximum). As can be seen in the above table, under normal load flow conditions, the voltage measured on the high-voltage busbar of the modeled wind power plant is at 1.086 per unit, therefore acceptable.

Another quantity specified by the grid codes is the operating frequency of a renewable power plant. It is stated that the renewable power plant can be allowed to run continuously at the frequency range between 49 Hz to 51 Hz. The frequency of the modeled wind power plant does not violate the continuous operating range specified by the grid codes, as it is at 50 Hz under normal operating conditions.

V.   CONCLUSIONS

This part of the paper puts its focus on the modeling of a wind power plant (WPP) using the literature and theoretical framework covered in Part 1. In this part, the modeling of a complete wind power plant is presented. The load flow of the wind power plant is done for the aim of the grid compliance test. Under this test, the mechanical and electrical quantities are monitored while the wind power plant is operated at a steady state. In terms of the grid compliance test, the electrical quantities are monitored at the sending and the receiving end terminals, since the wind power plant model consists of a transmission line system. The results show that the wind power plant operation complies with the grid codes. Part 3 covers the operation of the wind power plant under the conditions of grid-connected mode.

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