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Title: Maximization of Energy Capture of Passive, Variable-Speed Wind-Turbine Generator

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This thesis presents and examines the concept that the output of a wound-rotor induction generator (WRIG) can be limited by means of linking to external impedances for wind-turbine generating system application.

An 80kW-WRIG is simulated as a model to examine the control of the output power vs. speed characteristic. Model of WRIG derived from per phase equivalent circuit is organized, then it is estimated how much external impedances affect the characteristic of output power for it to approach to a typical wind-turbine curve. Practical tests are performed using 80kW-WRIG in testing lab to validate the simulation data. In addition, a smaller WRIG, connected on same shaft as 80kW-WRIG, is designed to extend the range of wind speed. Also external impedances with smaller WRIG are chosen to extract optimum power from wind-turbine.

Finally, passively controlled tandem WRIGs are shown to have the capability to optimize wind-turbine energy extraction when controlled entirely by external impedances.

# Maximization of Energy Capture of Passive, Variable-Speed Wind-Turbine Generator

by

Fuminao Kinjo

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Dean of the Graduate School

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Maximization of Energy Capture of Passive, Variable-Speed Wind-Turbine Generator

## 1. Introduction

Producing energy is one of the necessities of our modern industrialized life. We are gradually approaching an energy crisis that could threaten our society if we continue producing electricity solely by our conventional generating systems using fossil fuels. Also, energy generation system from fossil fuel undoubtedly has an effect on the environment, as recognized by the Kyoto protocol [1]. Options to resolve these problems are our significant mission.

Renewable energy, an alternative energy to conventional generating systems, is considered as one of the most effective ways to resolve these issues. However, most renewable energy has some concerns and perhaps technical problems to be overcome before applying to utility energy sources. For instance, reliability, high capital and maintenance cost, lower efficiency and poor infrastructure inhibit them from spreading out all over the world in a completely decentralized manner.

Wind power, one of the most important examples of renewable energy, is spotlighted as a prospective generating system since it is expected to have higher efficiency and consequently more reasonable production cost compared to other renewable systems. As shown in FIGURE 1.1 [2], middle west part of United States can be expected to obtain strong wind constantly. In Oregon, 6.4~7.5m/s average wind can be observed. Wind turbines of any appreciable rating must be large and their speed must be variable. Thus their output power needs to be processed to become an appropriately stabilized power source compatible with utility electricity. Various methods [3] for this correction are introduced to have been adopted to keep output power stable, as shown in FIGURE 1.2.

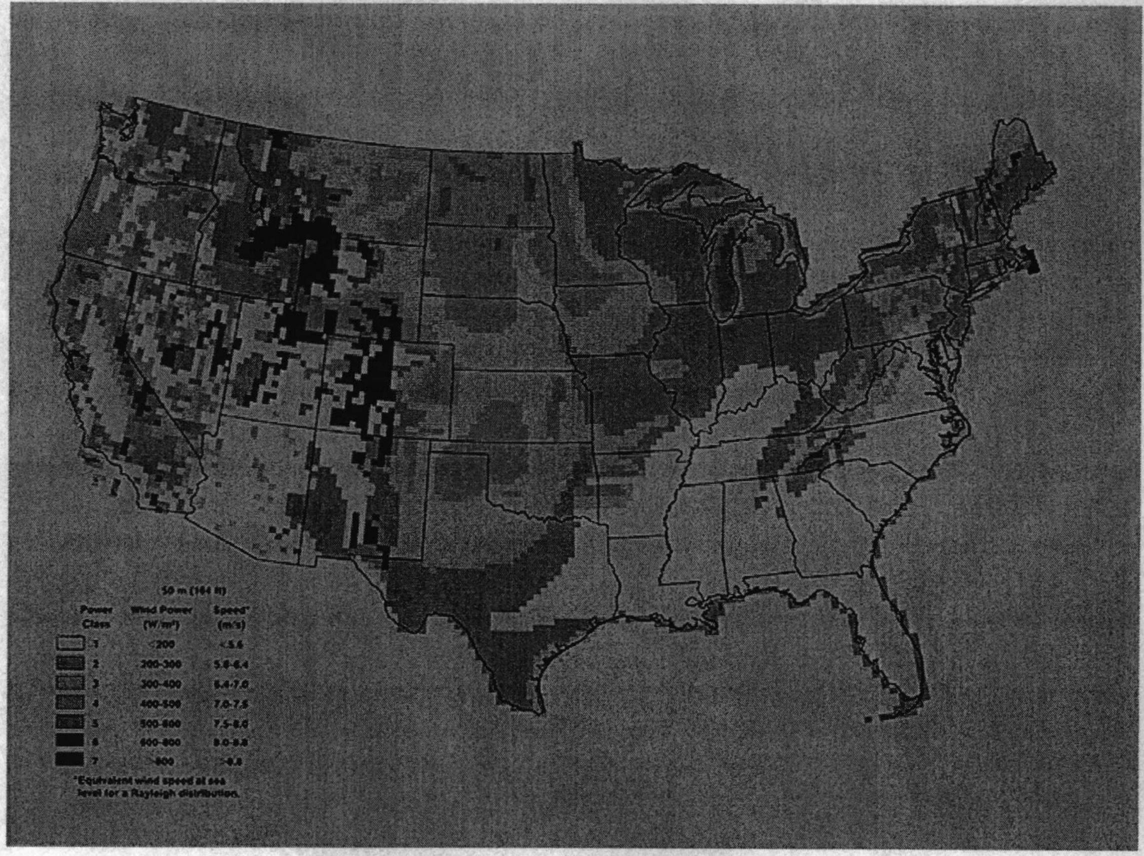


FIGURE 1.1: United States Annual Average Wind Power (Renewable Resource Data Center, 1986)

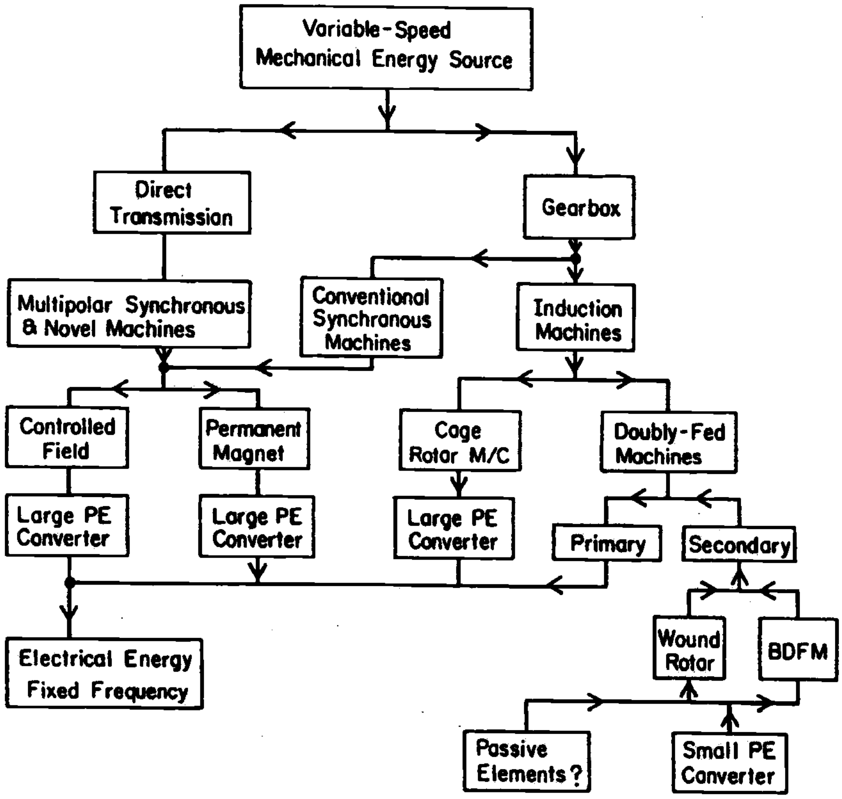


FIGURE 1.2: Alternative Energy Conversion Processes

1) Fixed speed (Squirrel-cage induction generator) by turbine adjustment such as spoilers, blade pitch control or mechanical brakes
2) Squirrel-cage induction generator producing variable frequency and conversion to 60Hz by inverter (FIGURE 1.3)
3) Synchronous generators (Both wound-field and permanent magnet) (FIGURE 1.4 and FIGURE 1.5)
4) Wound-rotor induction generator (WRIG) with rotor connected slip-frequency inverter (FIGURE 1.6)

5) The passively controlled induction generator (FIGURE 1.7 and FIGURE 1.8)

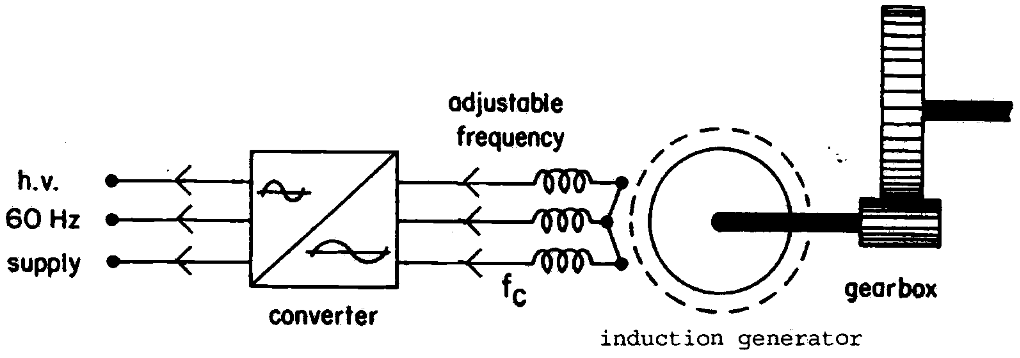


FIGURE 1.3: Cage-Rotor Induction Generator system

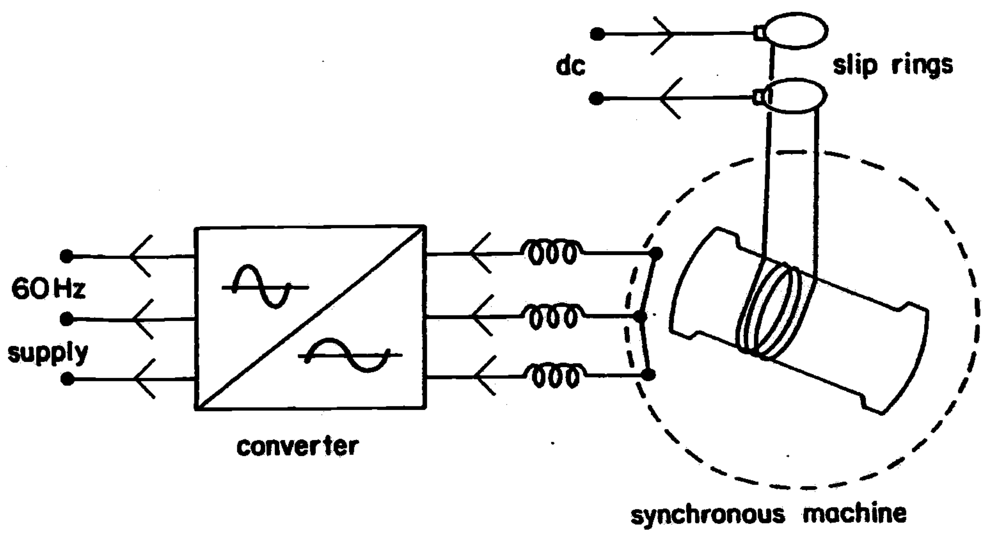


FIGURE 1.4: Wound Field Synchronous Generator system

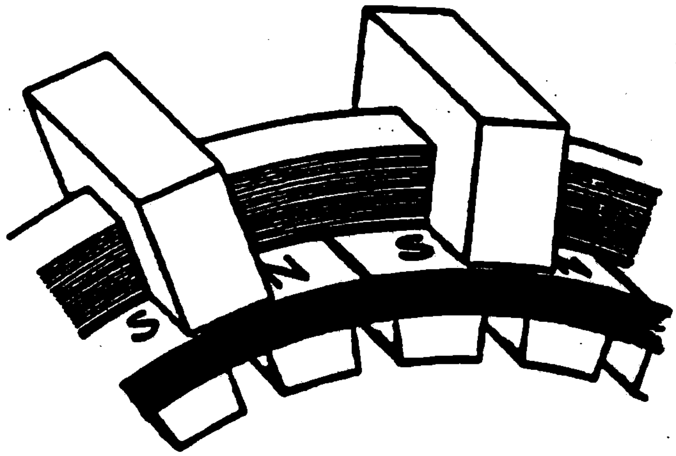


FIGURE 1.5: Example of Multipolar Permanent Magnet system

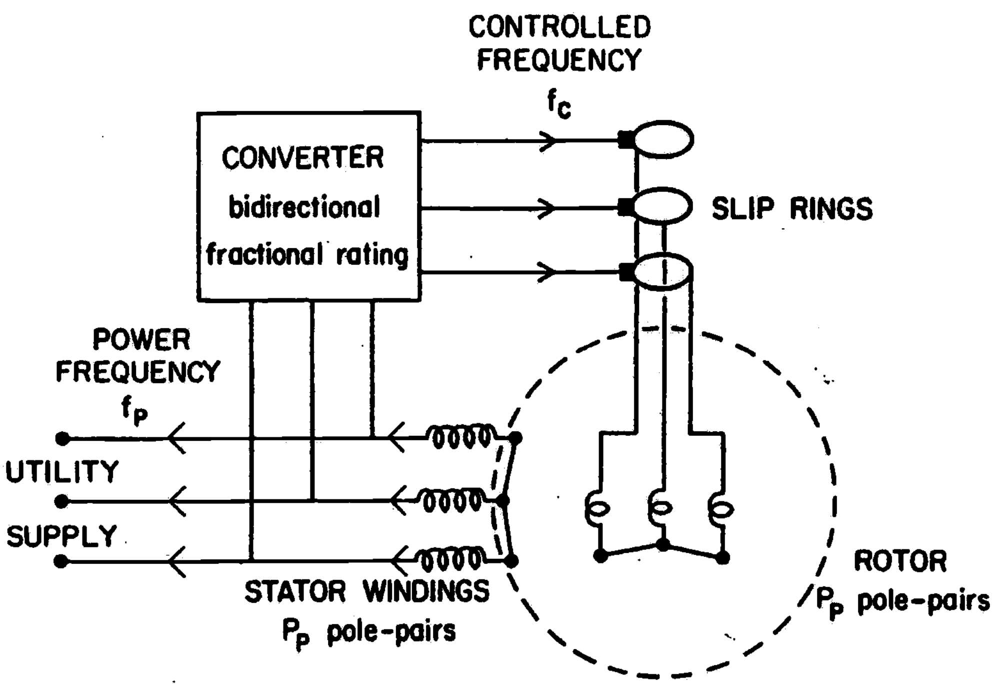


FIGURE 1.6: Wound-Rotor Doubly-Fed Machine system

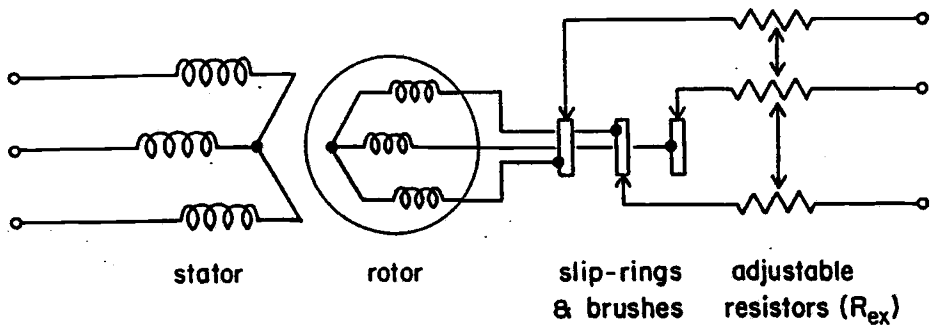


FIGURE 1.7: Controlled External Rotor Resistance system

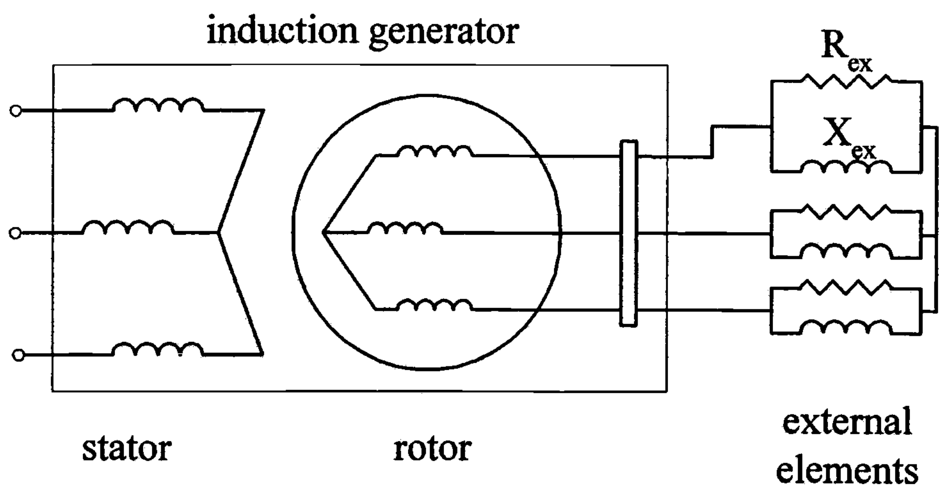


FIGURE 1.8: Passively Controlled variable-Speed Generation system

System 1) will have a short life and high cost to maintain the system because this braking system causes mechanical stress.

The biggest issue about inverter methods of 2) -4) is high cost, it needs a rectifier and two inverters. Also, the fact that power electronics may introduce harmonic distortion of the alternating current in the electrical grid, thus reducing power quality. Especially, the synchronous machine's construction is demanding and expensive (FIGURE 1.5) since its dimensions are bigger than those of a comparably rated induction machine. Moreover, the excitation system, which is essential for starting, is more complicated than that of the induction generator. System 5) is the system to be controlled by adding several impedances to the rotor-circuit, therefore it is very simple in structure and potentially low cost. In fact, literature [3-4], several books [5-7] and patents [8-11] were published regarding to this project. This thesis will focus on this system to find optimized model and control WRIG characteristics using external R&L&C because of its significantly simple electric circuit and lower cost.

The main purpose of the thesis is to describe, analyze, and provide practical proof of the ability to limit output power by connecting external impedances to the rotor circuit of an induction generator in the case where the wind turbine runs over nominal speed. Hereby, it can prevent damage to the generator windings and the loss of output. Appropriate impedance values for the rotor-connected external elements are evaluated by simulation result in Excel and MATLAB [12]. These indicate that it is possible to control induction generator effectively in this manner. Then, the result can be demonstrated by practical tests using an 80kW-WRIG in the Motor Systems Resource Facility (MSRF) in Oregon State University.

The MSRF includes a 300HP test bed and a 15HP test bed and control facilities to perform motor and generator tests (FIGURE 1.9). An auto-transformer, an adjustable power source arbitrary waveform generator and controllable Dynamometer (Dyno) contribute to the various test capabilities. A variety of tests are demonstrated such as no-load test, blocked rotor test, load efficiency test and so on. The 80kW-WRIG, used for this project, is coupled with the Dyno that is able to control it in either speed or torque mode on the 300HP test bed. Power for the generator is provided by an auto-transformer which enables the rated condition operation. Application of rated voltage to the stator circuit of the generator enables it to accelerate up to close to synchronous speed, which is 1200rpm. In this condition, this generator is running as a motor with no-load. The Dyno can then freely supply to this 80kW-WRIG the mechanical power using speed mode control. The generator test is demonstrated for external impedances which are calculated to produce ideal values required for practical wind turbine systems based on simulation data using Excel and MATLAB. First, the 80kW-WRIG was tested with external rotor connected inductance and resistance and the demonstrated performance were compared to simulation data. These components were previously demonstrated to extend the characteristic performance. The simulation model and testing are used in the current investigation to check on the validity of the circuit. Subsequently, the appropriate model for developing alternative generator to suit wind turbine characteristics is indicated by adding extra resistance and capacitance to the rotor circuit. Finally an additional 8 pole-WRIG is designed to be coupled this generator system based on 80kW-WRIG data. This designed WRIG is assumed to use lower speed range than 80kW-WRIG. Practically, the combination of these two WRIG will enable a fully adapted generator speed profile to accommodate wide variations of wind speed.

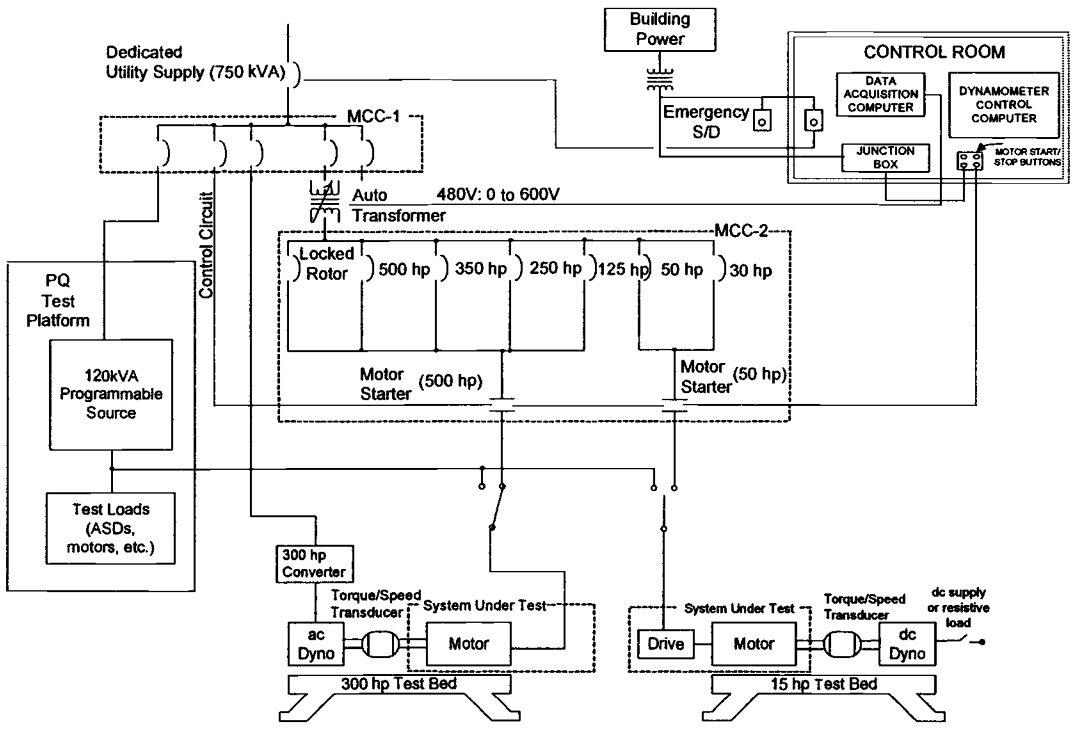


FIGURE 1.9: Motor Systems Resource Facility in OSU

# 2. Turbine Considerations

## 2.1: General Wind-Turbine Characteristic

Wind-turbines have the potential to be used as a significant resource to generate a large amount of energy. According to references [13-15], this power is influenced by a variety of conditions such as the turbine size, wind speed, temperature, air pressure and so on. The tip-speed ratio, $\lambda$, represents the ratio of wind speed and tip speed of the turbine blades. It is also the critical parameter to determine the characteristic of wind turbine. The following parameters, as described in reference [15], are used to determine a characteristic of wind-turbine in this project. Then, the wind-turbine power is calculated from kinetic energy law in a parcel of air of mass using these parameters. Naturally, the condition that wind is assumed to face on the surface of windmill is considered to cause high efficiency for wind-turbine system.

| Parameter | Concept |
|---|---|
| A | Cross-Sectional Swept Area of Turbine [$m^2$] |
| $p$ | The Air Pressure in kilopascal [kpa] |
| T | Air Temperature in Kelvin [K] |
| $\lambda$ | Tip Speed Ratio |
| $r_m$ | Maximum Radius of Turbine [m] |
| $\omega_m$ | Angular Velocity of Turbine [rad/s] |
| N | Shaft Speed [rpm] |
| u | Undisturbed Wind Speed Range [m/s] |
| $a_g$ | Turbine Shaft to Generator Rotor Gear Ratio |
| $\rho$ | Air Density [$kg/m^3$] |
| x | Thickness of the Parcel of the Meters [m] |
| U | Kinetic Energy [J] |
| $P_w$ | Output Power of Wind-Turbine [W] |
| $C_p$ | Coefficient of Practical Wind Performance |

TABLE 2.1: Wind-Turbine Parameters

Kinetic energy (U) in a parcel of air mass (m) of wind-turbine is given as follows,

$$U = \frac{1}{2} mu^2 = \frac{1}{2} (\rho Ax) u^2 \quad [J] \tag{2.1}$$

The power in the wind is the time derivative of the above kinetic energy

$$P_w = \frac{dU}{dt} = \frac{1}{2} \rho Au^2 \frac{dx}{dt} = \frac{1}{2} \rho Au^3 \ [W] \tag{2.2}$$

In order to obtain air density, it needs to be computed with some presumed air conditions. Air density equation will be derived from the laws of Charles and Boyle, which is the following,

$$pV = nRT \tag{2.3}$$

In this equation, p is a pressure [Pa], V is the gas volume [$m^3$], n is the number of kiromoles. For standard condition of 273 [K] and 1 [atm], 1[kmol] of gas occupies 22.414[$m^3$], and the universal gas constant is 8314.5 J/(kmol K). From these data, a pressure can be shown as follows,

$$p = \frac{nRT}{V} = \frac{1 \cdot 8314.5 \cdot 273.15}{22.414} = 101{,}325 \text{ [pa]} \tag{2.4}$$

Assuming the average molecular mass for air (as a mixture of oxygen and nitrogen) is 28.97, the density $\rho$ of a gas is computed by calculating by

$$\rho = \frac{m}{V} \text{ [kg/m}^3\text{]} \tag{2.5}$$

Equation (2.3) is applied to (2.5), then $\rho$ is indicated as follows,

$$\rho = \frac{mp}{nRT} = \frac{3.484p}{T} \text{ [kg/m}^3\text{]} \tag{2.6}$$

Equation (2.6) is calculated as 1.293kg/$m^3$ using (2.4), so in this thesis, we will assume these values as a standard conditions for dry air.

Equation (2.2) combining with (2.6) leads to

$$P_W = \frac{1}{2} \rho A u^3 = \frac{1.742pAu^3}{T} \text{ [W]} \tag{2.7}$$

Standard an air pressure (2.4) and standard temperature 273[K] indicates (2.7) as

$$P_w = 0.647Au^3 \text{ [W]} \tag{2.8}$$

Generally, wind turbine characteristic in terms of output power is expressed as (2.8), which shows that it is proportional to the cubed of wind speed. Practically, the actual mechanical output power of wind-turbine to be able to extract from the power in the wind is given as

$$P_m = 0.647Au^3 C_p \text{ [W]} \tag{2.9}$$

Coefficient of practical wind performance, $C_p$, depends on the wind speed, and pitch angle and tip-speed ratio. FIGURE 2.1 is one of the examples extracted to show a variety of values due to tip-speed ratio. The most effective number of $C_p$ is shown as approximately 0.35 in this model. Since the configuration of wind-turbine and induction generator considering external impedances to limit output-power is drawn as FIGURE 2.2, it is desirable that wind-turbine output-power and induction generator input power is as close as possible such as FIGURE 2.3 ideally.

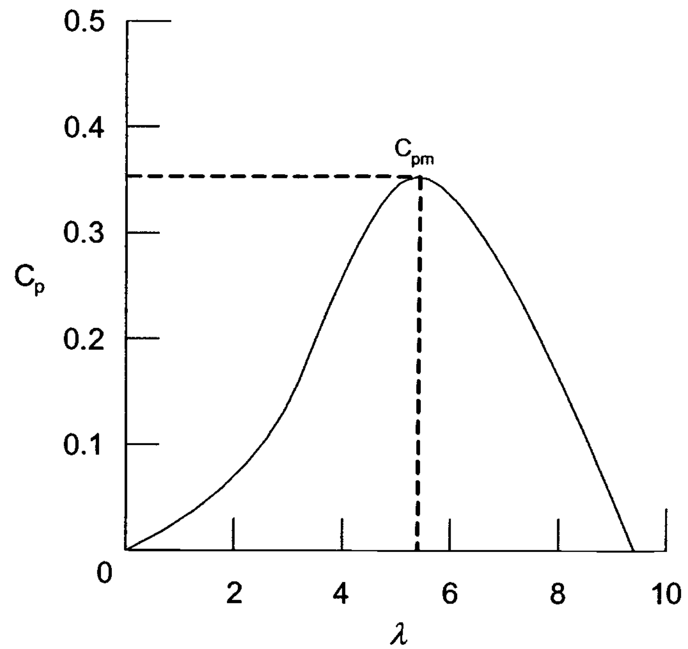


FIGURE 2.1: Coefficient of Performance Cp vs Tip-Speed Ratio

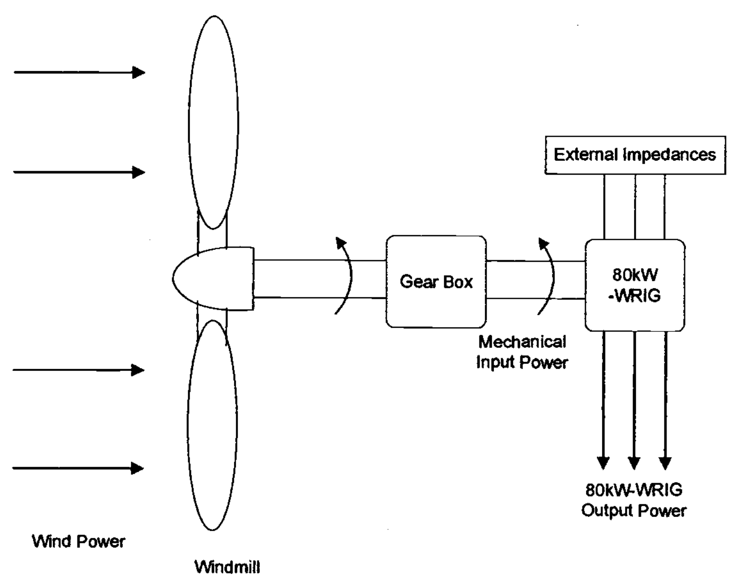


FIGURE 2.2: Configuration of Wind-Turbine and Induction

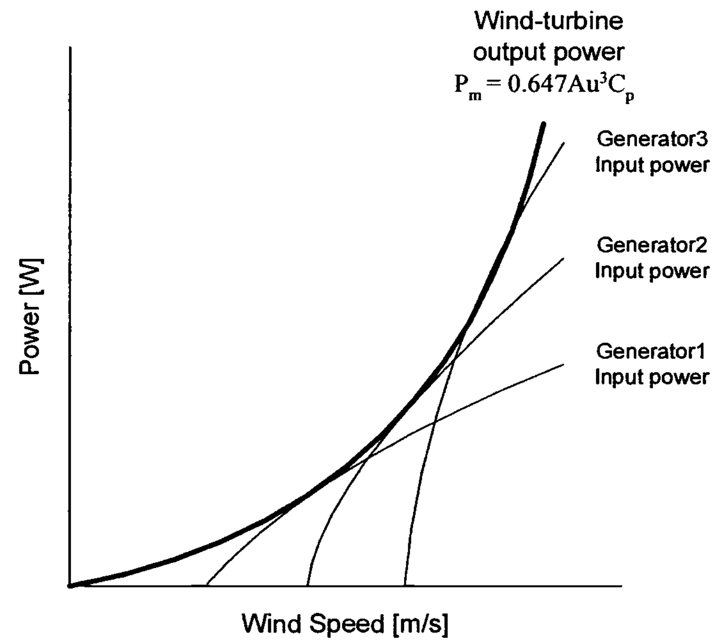


FIGURE 2.3: General Wind-Turbine and Ideal Generator Characteristics

## 2.2: Induction Generator Selection

WRIG wind-turbine applications are chosen with consideration for various operational parameters. Actual mechanical output power of wind-turbine, $P_m$, corresponds to the input power of induction generator. In order to select appropriate induction generator, it should be chosen and needs to be controlled to adapt it to the wind-turbine characteristic. Also the power range of generation can be extended by combination with additional generators of different power rating and pole number for this wind-turbine. Also the gear ratio and tip-speed ratio should be appropriately selected. Angular velocity $\omega_m$ is calculated from wind speed, maximum radius of blade and tip ratio as follows,

$$\omega_m = \frac{\lambda u}{r_m} \text{ [rad/s]} \tag{2.10}$$

Shaft speed is

$$N_{sh} = \frac{60\omega_m}{2\pi} \text{ [rpm]} \tag{2.11}$$

The generator's rotor speed following the gear box ratio is calculated as

$$N = \frac{1}{a_g} N_{sh} \text{ [rpm]} \tag{2.12}$$

Hereby, the appropriate WRIG including pole number and speed range can be estimated based on expected wind speed. Consequently, we need to design the model of the input power of 80kW-WRIG adding external impedances to rotor circuit to correspond to arbitrary wind turbine power that is proportional to speed-cubed and verify this model by practical tests. Afterwards, appropriate wind-turbine specification will be determined based on these data. Practically, generator mechanical losses and gear loss exist. The generator mechanical loss is included, but gear loss is neglected since the value of that is not the main focus of this project.

# 3. Theoretical Model

## 3.1: 80kW-WRIG with External Resistance and Inductance (with R&L)

First, external resistance and inductance are connected to the rotor circuit in the steady state equivalent circuit as covered in previous literature [4]. Here, it is verified how external resistance and inductance influence on the characteristic of WRIG. Let us assume the required range of this generator speed as from 1200 rpm to 1500rpm. This WRIG's rated speed (100% load with shorted rotor circuit) is specified as 1212 rpm. Thus, external impedance must be employed to extend this rated speed up to 1500rpm. An equivalent circuit per phase with external impedance is utilized to simplify the simulation shown as follows,

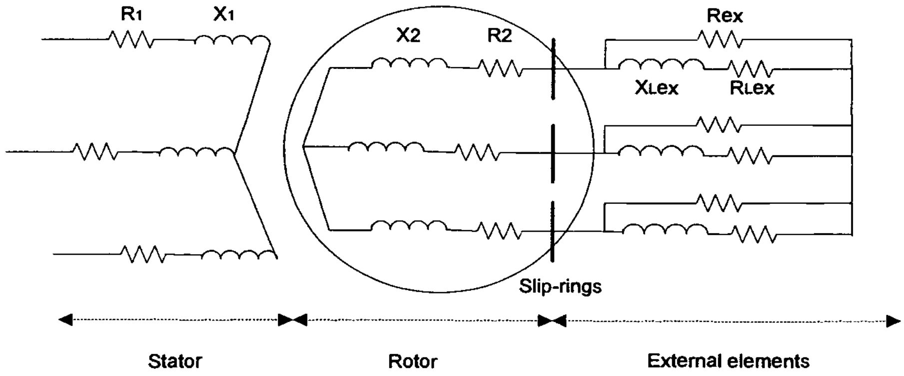


FIGURE 3.1: WRIG with External R&L

An equivalent circuit per phase to calculate is shown as follows,

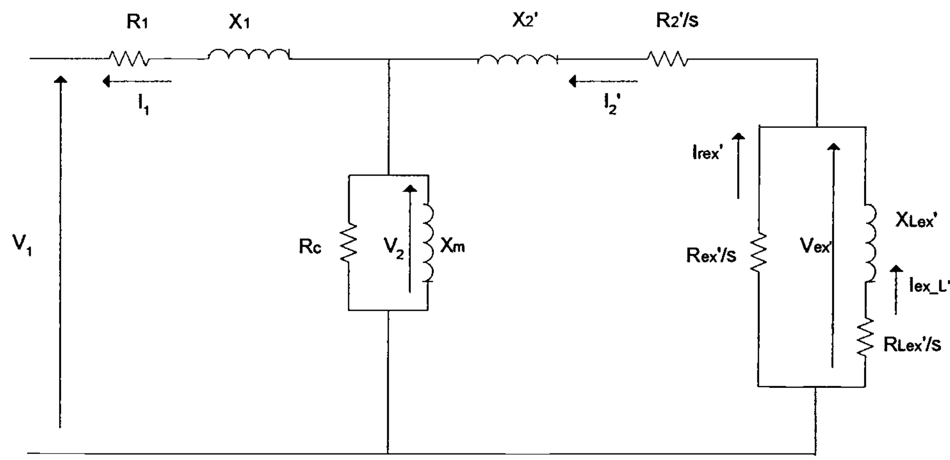


FIGURE 3.2: Per-phase Equivalent Circuit with External R&L

| Parameter | Meaning |
|---|---|
| a | Turns ratio of Rotor to Stator |
| $R_1$ | Stator leakage resistance[ Ω ] |
| $X_1$ | Stator leakage reactance [ Ω ] |
| $R_2$' | Rotor leakage resistance referred to stator [ Ω ] |
| $X_2$' | Rotor leakage reactance referred to stator [ Ω ] |
| $L_2$ | Rotor pure inductance [H] |
| $R_c$ | Stator core loss resistance [ Ω ] |
| $X_m$ | Mutual reactance [ Ω ] |
| $R_{ex}$' | External resistance referred to stator [ Ω ] |
| $X_{Lex}$' | External reactance referred to stator [ Ω ] |
| $L_{ex}$ | External pure inductance [H] |
| $R_{Lex}$' | External resistance of inductance referred to stator [ Ω ] |

TABLE 3.1: Parameter Indication of Per-phase Equivalent Circuit

In order to obtain, the following tests were performed

1) DC measurement test

2) Blocked rotor test

3) Non load test

From these test data, the actual parameters of 80kW-WRIG were computed as follows,

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| a | 2.486 | $X_1$ | 0.2842[Ω] |
| $R_1$ | 0.0220[Ω] | $X_2$' | 0.2842[Ω] |
| $R_2$' | 0.0386[Ω] | $L_2$ | $4.659\times 10^{-3}$[H] |
| $R_c$ | 149.9802[Ω] | $X_m$ | 7.8912[Ω] |

TABLE 3.2: Parameters of 80kW-WRIG

In order to obtain characteristic of this induction generator, the following calculation is performed. First, total external impedance $Z_3$ is evaluated as follows,

$$Z_3 = \frac{\left\{\dfrac{R'_{Lex}(R'_{Lex}+R'_{ex})}{s^2}+X'^2_{Lex}\right\}\dfrac{R'_{ex}}{s}}{\left(\dfrac{R'_{Lex}+R'_{ex}}{s}\right)^2+X'^2_{Lex}} + j\frac{\dfrac{X'_{Lex}R'_{Lex}R'_{ex}}{s^2}}{\left(\dfrac{R'_{Lex}+R'_{ex}}{s}\right)^2+X'^2_{Lex}} \tag{3.1}$$

$Z_2$, impedance combined the rotor impedance with $Z_3$, is computed as follows,

$$Z_2 = \frac{R'_2}{s} + \frac{\left\{\dfrac{R'_{Lex}(R'_{Lex}+R'_{ex})}{s^2}+X'^2_{Lex}\right\}\dfrac{R'_{ex}}{s}}{\left(\dfrac{R'_{Lex}+R'_{ex}}{s}\right)^2+X'^2_{Lex}} + j\left[X'_2 + \frac{\dfrac{X'_{Lex}R'_{Lex}R'_{ex}}{s^2}}{\left(\dfrac{R'_{Lex}+R'_{ex}}{s}\right)^2+X'^2_{Lex}}\right] \tag{3.2}$$

$Z_m$, impedance combined the mutual reactance with core resistance, is calculated as

$$Z_m = \frac{jR_c X_m}{R_c + jX_m} = \frac{R_c X_m^2}{R_c^2 + X_m^2} + \frac{jR_c^2 X_m}{R_c^2 + X_m^2} \tag{3.3}$$

$Z_1$, all impedance from stator side, is computed as follows,

$$Z_1 = R_1 + jX_1 + \frac{Z_2 Z_m}{Z_2 + Z_m} \tag{3.4}$$

$I_1$, stator current, calculated such as

$$I_1 = \frac{V_1}{Z_1} \tag{3.5}$$

$V_2$, voltage across mutual impedance and rotor impedance, is expressed from stator voltage $V_1$

$$V_2 = V_1 + I_1(R_1 + jX_1) \tag{3.6}$$

$I_2'$, rotor current referred to stator, is indicated as

$$I_2' = \frac{V_2}{Z_2} \tag{3.7}$$

T, total torque, is given using real part of $Z_{2r}$ and phase speed $\omega$

$$T = \frac{3(1-s)\left|I_2'\right|^2 Z_{2r}}{\omega} \tag{3.8}$$

$P_m$, mechanical input power, is indicated as

$$P_m = 3(1-s)\left|I_2'\right|^2 Z_{2r} \tag{3.9}$$

p.f., power factor, is given from current of real part

$$\text{p.f.} = \frac{I_{1r}}{|I_1|} \tag{3.10}$$

$P_e$, electrical output power, is calculated as

$$P_e = 3|I_1||V_1|\cos\theta \tag{3.11}$$

From the above calculation, we put some external parameters values using Microsoft Excel to meet slightly higher output power than that of 100% load at 1320 rpm, which is 10% higher speed than synchronous speed. Appropriate external parameters were chosen to meet the above conditions after all equations are included in a Microsoft Excel file. Then, the following parameters were selected to demonstrate the extension of output power against speed.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $R_{ex}$ | 1.170 [Ω] | $R_{Lex}$ | 0.638 [Ω] |
| $R_{ex}'$ | 0.189 [Ω] | $R_{Lex}'$ | 0.103 [Ω] |
| $X_{Lex}'$ | 26.900[Ω] | ——— | ——— |
| $L_{ex}$ | 0.441 [H] | ——— | ——— |

TABLE 3.3: Parameters of External R&L

The following graph represents the result of characteristic of this generator with shown external impedance.

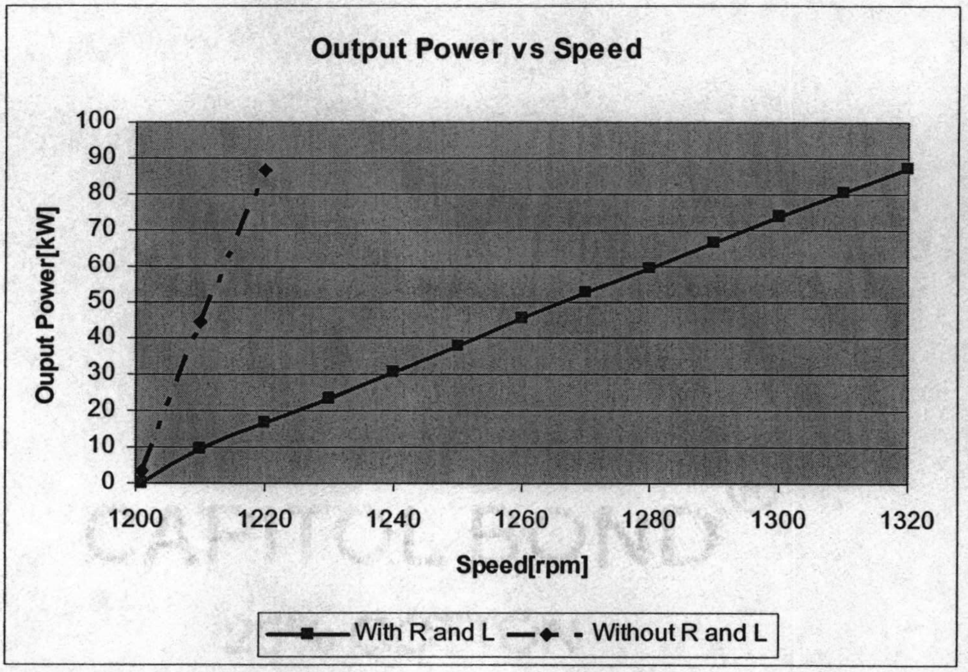


FIGURE 3.3: Output Power Characteristic of 80kW-WRIG with External R&L

Obviously, the range of output power is extended compared to that of shorted rotor circuit (Without R and L). However, the graph to limit the output power to approach to the characteristic of wind-turbine was not founded no matter what type of valued of these impedances.

3.2: 80kW-WRIG with External Resistance, Inductance and Capacitance (with R&L&C)

The characteristic of output power could be extended around 100% load point up to 1500rpm in section 3.1. However, ideal graph to fit wind-turbine characteristic like Fig 2.1 should increase more steeply at lower speed range and less steeply at higher speed range effectively. The calculation will be shown as well as that of section 3.1.

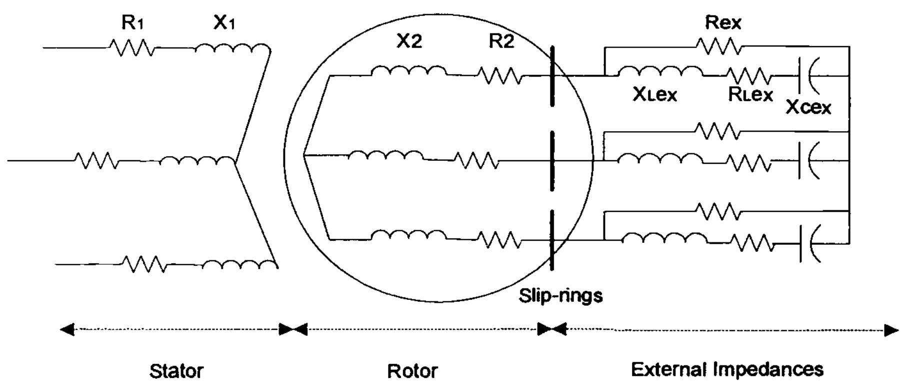


FIGURE 3.4: WRIG with External R&L&C

An equivalent circuit per phase to calculate is shown as follows,

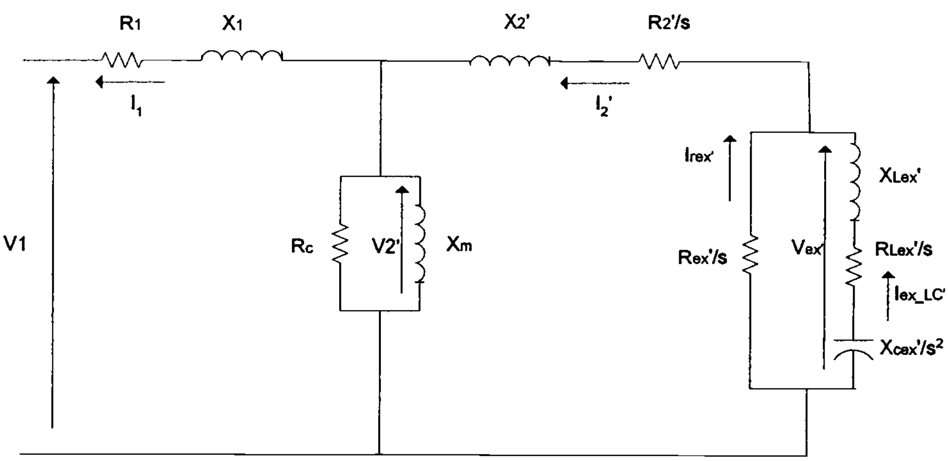


FIGURE 3.5: Per-Phase Equivalent Circuit with External R&L&C

$X_{Cex}$' stands for capacitive reactance[ Ω ] connected as one of the external impedance components. The calculation data will be expressed as follows based on these parameters,

$$Z_3 = \frac{\left\{\frac{R'_{Lex}(R'_{Lex}+R'_{ex})}{s^2} + (X'_{Lex} - \frac{X'_{Cex}}{s^2})\right\}\frac{R'_{ex}}{s}}{(\frac{R'_{Lex}+R'_{ex}}{s})^2 + (X'_{Lex} - \frac{X'_{Cex}}{s^2})^2}$$

$$+j\,\frac{\left\{\frac{X'_{Lex}(R'_{Lex}+R'_{ex}) - R_{ex}(X'_{Lex} - \frac{X'_{Cex}}{s^2})}{s}\right\}\frac{R'_{ex}}{s}}{(\frac{R'_{Lex}+R'_{ex}}{s})^2 + (X'_{Lex} - \frac{X'_{Cex}}{s^2})^2} \quad (3.12)$$

$Z_2$, impedance combined the rotor impedance with $Z_3$, is computed as follows,

$$Z_2 = \frac{R'_2}{s} + \frac{\left\{ \frac{R'_{Lex}(R'_{Lex}+R'_{ex})}{s^2} + (X'_{Lex} - \frac{X'_{Cex}}{s^2})^2 \right\} \frac{R'_{ex}}{s}}{(\frac{R'_{Lex}+R'_{ex}}{s})^2 + (X'_{Lex} - \frac{X'_{Cex}}{s^2})^2}$$

$$+ j \left[ X'_2 + \frac{\frac{R'^2_{ex}(X'_{Lex} - \frac{X'_{Cex}}{s^2})}{s^2}}{(\frac{R'_{Lex}+R'_{ex}}{s})^2 + (X'_{Lex} - \frac{X'_{Cex}}{s^2})^2} \right] \quad (3.13)$$

Then, the rest of equation will be used as well as equation (3.3)-(3.11).

From these equations, we could estimate appropriate external impedance including capacitors as follows,

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $R_{ex}$ | 3.100 [Ω] | $L_{ex}$ | 0.441[H] |
| $R_{ex}$’ | 0.502 [Ω] | $X_{Lex}$’ | 26.901[Ω] |
| $C_{ex}$ | 500[μF] | $R_{Lex}$ | 14.000[Ω] |
| $X_{cex}$’ | 0.858 [Ω] | $R_{Lex}$’ | 2.265[Ω] |

TABLE 3.4: Parameters of External R&L&C

The following graph shows the characteristic of output power containing these values.

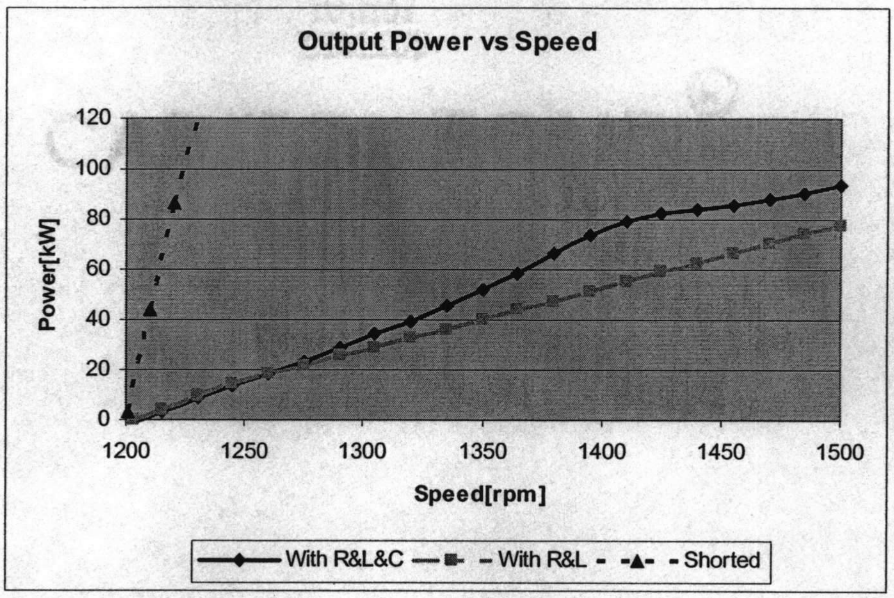


FIGURE 3.6: Output Power Characteristic of 80kW-WRIG with External R&L&C

The range of output power is extended compared to that of shorted-rotor WRIG as well. The graph of rotor-connected external impedances is controllable to be steady state adding capacitance. The graph with external R&L&C is not a straight line such as others. Also, R&L&C track is relatively higher than R&L though R&L values of both conditions are same. It is considered as that capacitance and inductance will have a resonance at some frequency since that of rotor circuit is changing with rotor speed. In fact, it is possible to alter this graph's top position for any values whichever we want. Thus, we can determine proper external elements values to optimize wind-turbine. The values of external impedances were determined to meet 115% load at 1500rpm in the simulation to optimize the induction generator's capacity with service factor 1.15.

3.3: Ideal Wind-Turbine Power Model for 80kW-WRIG

In this project, proper wind-turbine dimension is designed to meet the given generator power as a peculiar induction generator to analyze. The method to determine the characteristic of wind-turbine is the following,

1) A graph of induction generator including service factor is designed to meet maximum output power, 92kW at 1500rpm by choosing appropriate values of external impedances drawing input power of FIGURE 3.7.
2) Draw the graph of input power of generator since input power directly transformed from mechanical input power of wind-turbine
3) Determine parameters of wind-turbine arbitrarily to correspond to the maximum power point of the generator.

The input power graph of the generator is the follows,

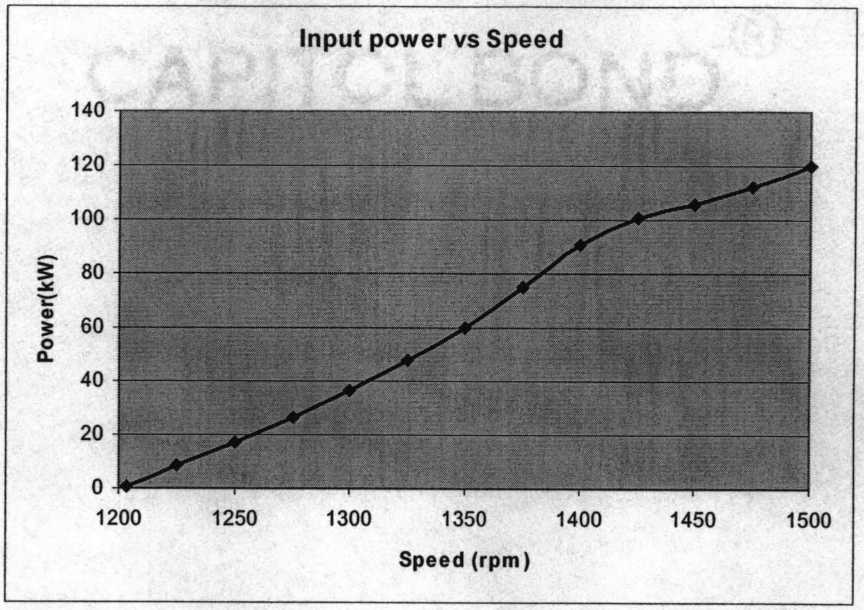


FIGURE 3.7: Input Power Characteristic of 80kW-WRIG with External R&L&C

The value of generator input power at 1500rpm is 119.8 kW. The following parameters were determined to correspond to the generator input power at 1500 rpm. Let us choose $C_p$ as a maximum constant value for any wind-speed.

| Parameter | Meaning | Values |
|---|---|---|
| A | Cross-Sectional swept of turbine area [m$^2$] | 512.2 |
| $p$ | The air pressure in kilopascal [kpa] | 101.3 |
| T | Air Temperature in Kelvin [K] | 273 |
| $\lambda$ | Tip speed ratio | 5.190 |
| $r_m$ | Maximum radius of turbine [m] | 13.55 |
| $\omega_m$ | Angular velocity of turbine [rad/s] | $\frac{2\pi N}{60}$ |
| N | Shaft speed [rpm] | $\frac{60\omega_m}{2\pi}$ |
| u | Undisturbed wind speed range [m/s] | 8.20- 10.25 |
| $a_g$ | Gear ratio: turbine shaft to generator rotor | 40 |
| $\rho$ | Air density [kg/m$^3$] | $3.485\frac{p}{T}$ |
| x | Thickness of the parcel of the meters [m] | x |
| U | Kinetic energy [J] | $\frac{1}{2}(\rho Ax)u^2$ |
| $P_w$ | Output Power of wind-turbine [W] | $\frac{1}{2}\rho Au^3$ |
| $C_p$ | Coefficient of practical wind performance | 0.35 |

TABLE 3.5: Wind-Turbine Parameters to fit in 80kW-WRIG

From these data, output power, $P_w$, is drawn as the following graph and be compared to simulation result of 80k-WRIG.

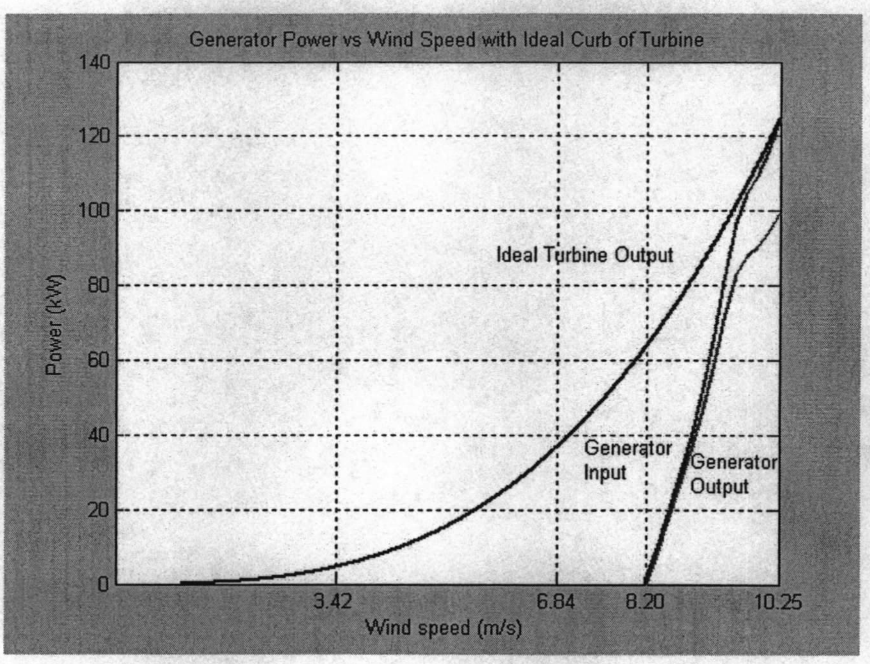


FIGURE 3.8: 80kW-WRIG Power with Ideal Curve of Turbine based on Calculation

This is the ideal wind-turbine power characteristic to fit in this 80kW-WRIG. This generator is able to cover the range 1200rpm to 1500rpm which is equivalent to 8.20m/s to 10.25m/s of wind speed. Another 8 pole generator, to cover lower side, will be designed afterwards.

# 4. Test Program

## 4.1: Test Configuration

The simulation described in Section 3 is to be demonstrated by the practical test. The MSRF prepared every equipment to perform this practical test using dynamometer, transducer, an adjustable speed drive control equipment, etc. The configuration is shown as FIGURE 4.1

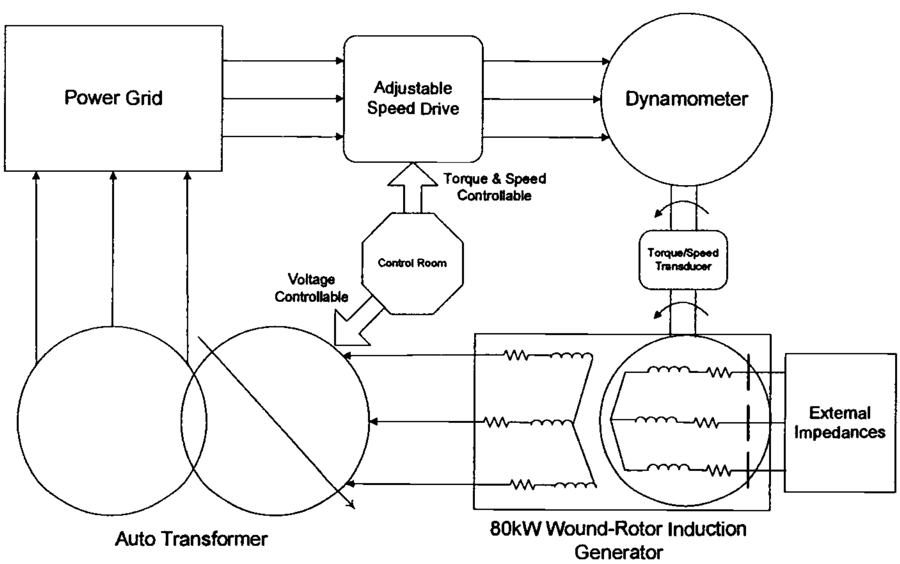


FIGURE 4.1: Test Configuration

The test was performed by these facilities. Speed and torque were measured by Lebow torque sensor model 1805-10k and speed/torque display instrument 7540-115 manufactured by ETN. This particular torque sensor was chosen based on the input power of the generator and its torque measurement was calibrated within 0.5% error. Electric data such as voltage, current, power factor in terms of necessities for analysis were measured by power analyzer model PM3300 manufactured by Voltech. The dynamometer was programmed at start to maintain the speed at 1200 rpm which is synchronous speed of WRIG. The power was supplied by power grid through auto transformer. Hereby, the WRIG started to spin as a motor obtaining the power from power grid. An output voltage is maintained as 480V, which is rated voltage of this generator, by adjusting secondary voltage of auto transformer while it is operating. The secondary voltage of auto transformer can be controlled by the data acquisition system programmed in C-language, located in the control room. After the WRIG was warmed up, the speed of dynamometer, which is controlled C-language configured of DOS, was increased in order that it should begin operation as a generator. Then, several points were plotted in terms of input power, output power, torque, stator current power factor and efficiency until the WRIG was producing 115% of its rated power, which is equivalent to 92kW. This was used for the limit of output power since service factor was shown as 1.15 by manufacturer.

## 4.2: Test with External R&L

Demonstration was performed to prove simulated data. First, external components should be prepared to connect with rotor circuit of WRIG. As an external resistance, the force-cooled box resistance in FIGURE 4.2 was used. Those resistance values were given by this resistance box, therefore, we checked these values by DC digital microhmmeter manufactured by NGI. On the other hand, the available inductance has been calibrated as specified in TABLE 4.1. In order to make sure their resistance values were correct, they were also checked by DC digital microhmmeter. After that, 3 phases AC voltage was supplied, then voltage, current and power were measured to calculate inductance values. Hereby these values were proved to correspond to the values shown on data sheet. In other words, the parameters determined in previous simulation were taken into consideration.

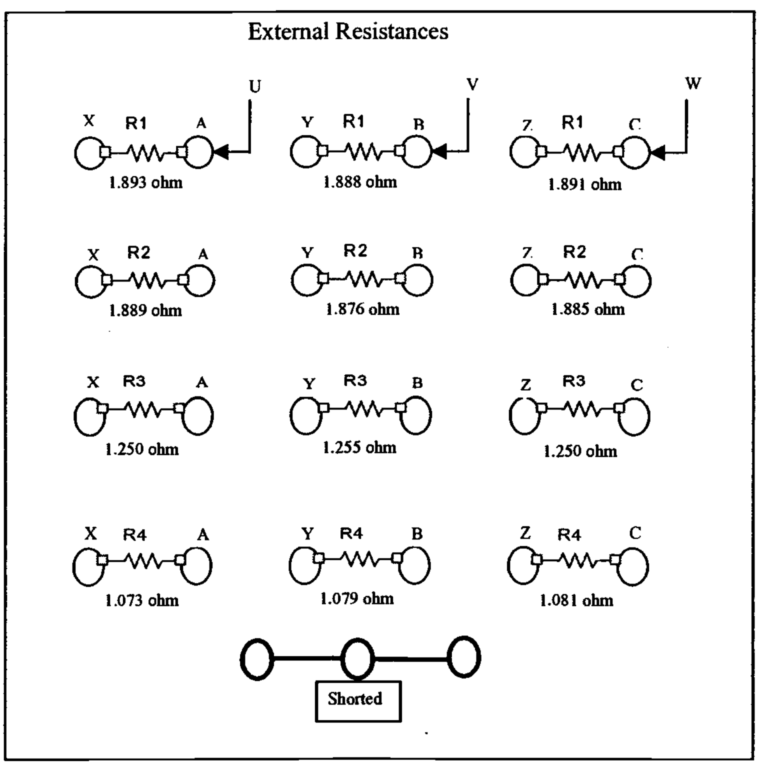


FIGURE 4.2: External Resistors Box

| Connection | Inductance (mH) | Resistance (ohms) |
|---|---|---|
| Connection1 | 137.4 | 0.385 |
| Connection2 | 229.8 | 0.451 |
| Connection3 | 296.5 | 0.506 |
| Connection4 | 368.7 | 0.572 |
| Connection5 | 441.2 | 0.638 |

TABLE 4.1: Inductance and Resistance Values for Various Connections

These external impedances will be connected such as FIGURE 3.1 and FIGURE 3.2. The following TABLE 4.2 shows test data, for 10% speed range.

| Speed [rpm] | Torque [Nm] | Input power [kW] | Output Power[kW] | Efficiency [%] | Stator Current [A] | Power Factor |
|---|---|---|---|---|---|---|
| 1201 | 23.5 | 2.96 | 1.38 | 46.7 | 32.8 | 0.051 |
| 1210 | 88.1 | 11.16 | 9.68 | 86.7 | 39.0 | 0.395 |
| 1220 | 149.1 | 19.05 | 17.15 | 90.0 | 44.7 | 0.461 |
| 1230 | 212.0 | 27.31 | 25.15 | 92.1 | 51.3 | 0.589 |
| 1240 | 273.0 | 35.45 | 32.22 | 90.9 | 58.2 | 0.669 |
| 1250 | 331.0 | 43.33 | 39.68 | 91.6 | 66.2 | 0.723 |
| 1260 | 396.3 | 52.29 | 47.81 | 91.4 | 75.3 | 0.764 |
| 1270 | 454.1 | 60.39 | 54.76 | 90.7 | 83.7 | 0.789 |
| 1280 | 518.0 | 69.43 | 62.60 | 90.2 | 93.2 | 0.809 |
| 1290 | 574.0 | 77.54 | 69.45 | 89.6 | 102.2 | 0.821 |
| 1300 | 636.0 | 86.58 | 76.84 | 88.8 | 111.7 | 0.830 |
| 1310 | 690.0 | 94.65 | 83.40 | 88.1 | 120.6 | 0.835 |
| 1320 | 747.0 | 103.25 | 90.10 | 87.3 | 129.8 | 0.838 |

TABLE 4.2: Test Data of 80kW-WRIG with External R&L

4.3: Test with External R&L&C

As well as for 4.2, the external impedances should be prepared to connect with rotor circuit of WRIG. In addition to the components we used in section 4.2, C and additional external R will be applied to rotor circuit. Especially, resistance of inductance $R_{Lex}$ will be determined by our inductance shown in TABLE 4.1. For instance, if inductance values is chosen as 441.2 [mH], resistance of inductance values should be fixed as 0.638 [ohms]. However, we need to add extra resistance to meet 14[ohms] as $R_{Lex}$ values since it was estimated as an appropriate values in previous simulation result described in section 3.2. Therefore, the difference in values (13.362 [ohms]) to meet the total of 14 ohms is provided by an adjustable resistance manufactured by POWEROHMS. The specification for this resistor is adjustability from 7- 14 ohms, 14A rated current. Since the resistance to fill this specification is large, POWEROHM assembled two resistances to meet our order. Capacitors manufactured by G.E. were used 50uF/370V-AC 60Hz types. 10 capacitors were connected parallel per phase to meet 500uF capacitor value shown in section 3.2. If these capacitors are connected in delta at rotor circuit to meet 500uF each phase, fewer capacitors are necessary than wye-rotor connection. However, voltage across capacitors with delta rotor connection will be $\sqrt{3}$ times higher than that of wye-rotor connection. The rated voltage of capacitors we own in MSRF is only 370V-AC. Simulation data shows that maximum voltage across capacitors could be 385V-AC which could threat our testing facilities due to over rated voltage. Therefore, we chose wye connection for capacitors rotor circuit.

Naturally, capacitance value was measured confirmed by the 4284A PRECISION LCR METER manufactured by HEWLETT PACKARD. The following table shows result of this test.

| Speed [rpm] | Torque [Nm] | Input power [kW] | Output Power[kW] | Efficiency [%] | Stator Current [A] | Power Factor |
|---|---|---|---|---|---|---|
| 1202 | 13.1 | 1.65 | 0 | 0 | 34.1 | 0.002 |
| 1225 | 73.6 | 9.44 | 7.91 | 83.7 | 36.2 | 0.262 |
| 1250 | 143.7 | 18.81 | 17.42 | 91.0 | 41.2 | 0.497 |
| 1275 | 213.3 | 28.48 | 26.19 | 92.0 | 48.0 | 0.654 |
| 1300 | 288.0 | 39.21 | 35.98 | 91.8 | 57.1 | 0.756 |
| 1325 | 366.0 | 50.78 | 45.75 | 90.1 | 67.0 | 0.820 |
| 1350 | 458.0 | 64.75 | 57.52 | 88.8 | 79.9 | 0.861 |
| 1375 | 563.0 | 81.06 | 70.89 | 87.4 | 96.1 | 0.882 |
| 1400 | 660.0 | 96.76 | 82.97 | 85.7 | 114.4 | 0.867 |
| 1425 | 700.0 | 104.45 | 87.91 | 84.2 | 125.5 | 0.837 |
| 1450 | 720.7 | 109.43 | 90.37 | 82.6 | 131.3 | 0.824 |
| 1475 | 751.0 | 116.00 | 94.17 | 81.2 | 137.3 | 0.825 |
| 1500 | 795.0 | 124387 | 99.62 | 79.8 | 144.4 | 0.827 |

TABLE 4.3: Test Data of 80kW-WRIG with External R&L&C

## 4.4: Graphical Comparison between Model Predictions and Test Results

### 4.4.1. With External R&L

The following graphs show comparison test results with model predictions.

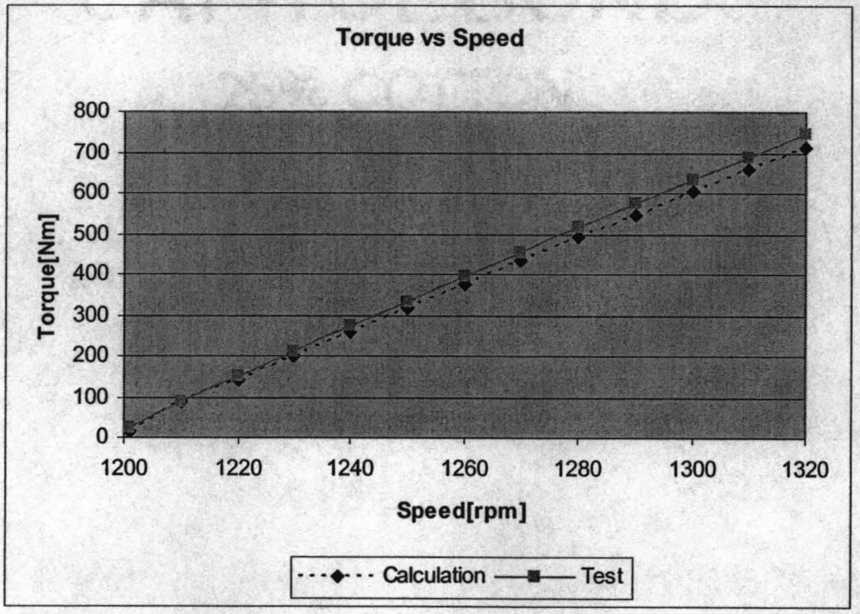


FIGURE 4.3: Torque Comparison between Simulation and Test of 80kW-WRIG with R&L

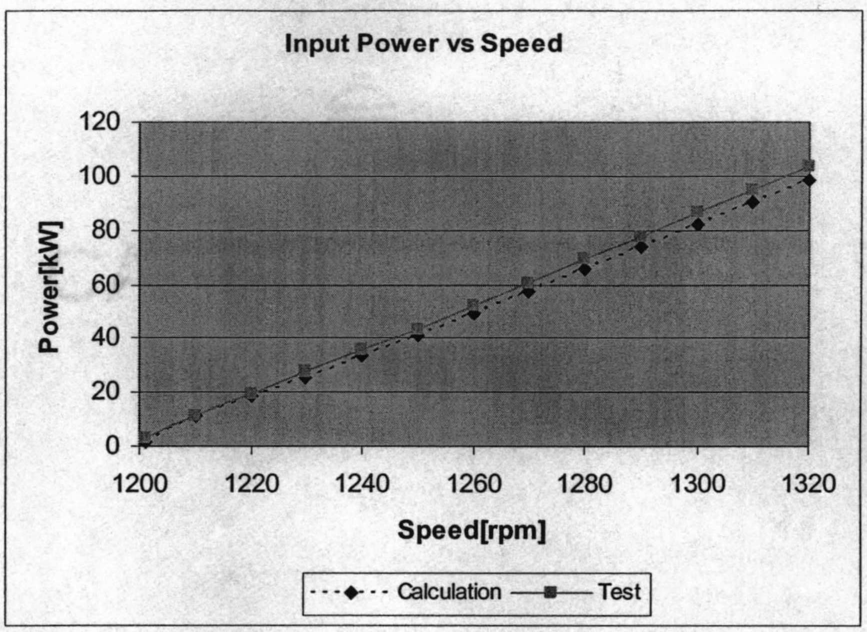


FIGURE 4.4: Input Power Comparison between Simulation and Test of 80kW-WRIG with R&L

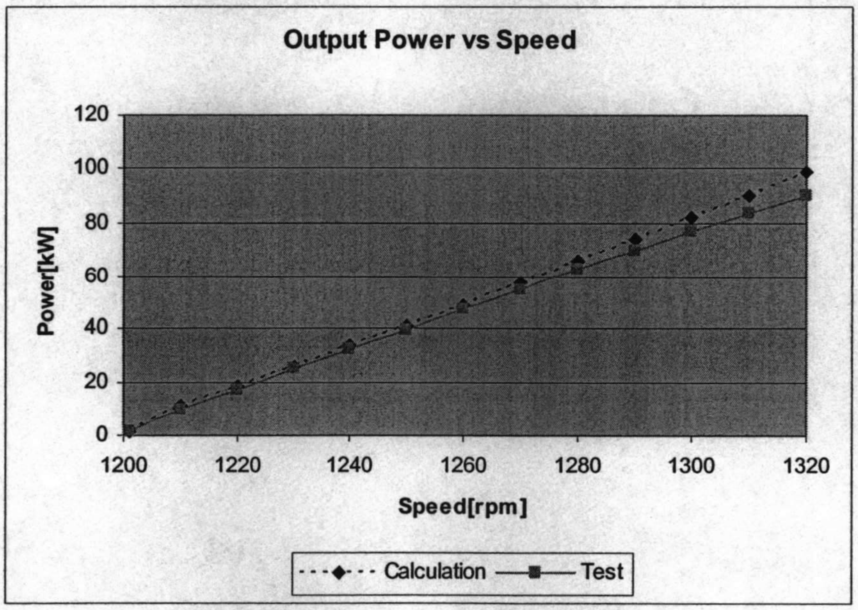


FIGURE 4.5: Output Power Comparison between Simulation and Test of 80kW-WRIG with R&L

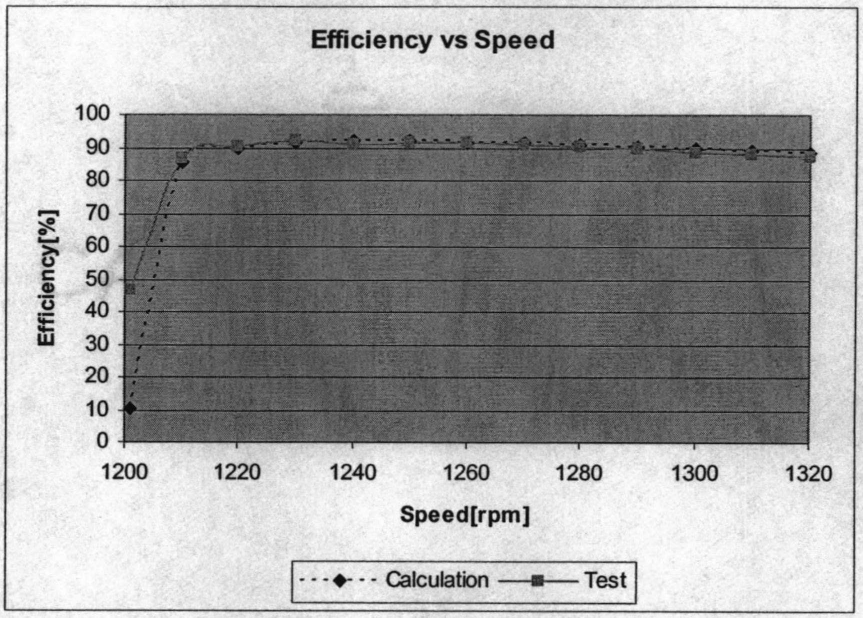


FIGURE 4.6: Efficiency Comparison between Simulation and Test of 80kW-WRIG with R&L

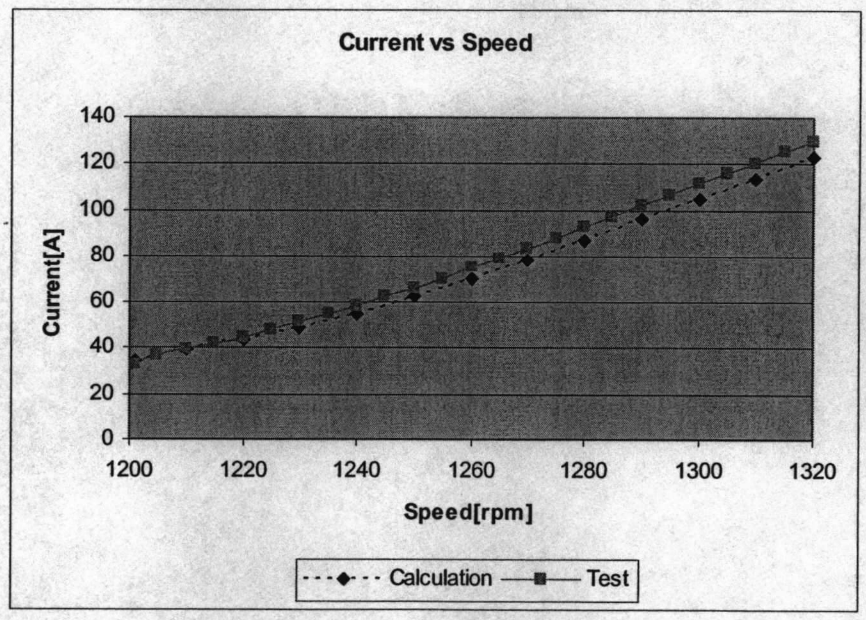


FIGURE 4.7: Stator Current Comparison between Simulation and Test of 80kW-WRIG with R&L

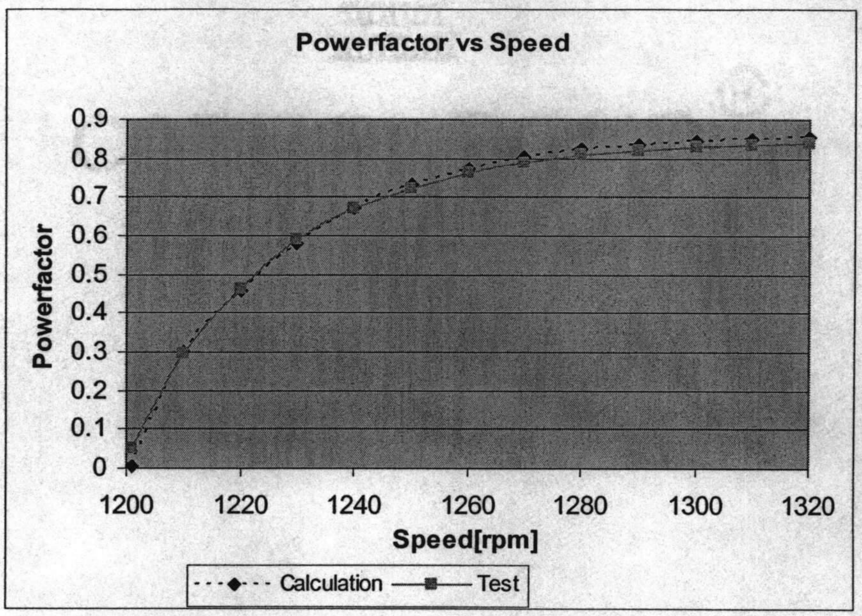


FIGURE 4.8: Power Factor comparison between simulation and test of 80kW-WRIG with R&L

Test results are obviously similar to those of simulation values. As expected, input and output powers had an extended characteristics compared to without external operation impedances.

4.4.2. With External R&L&C

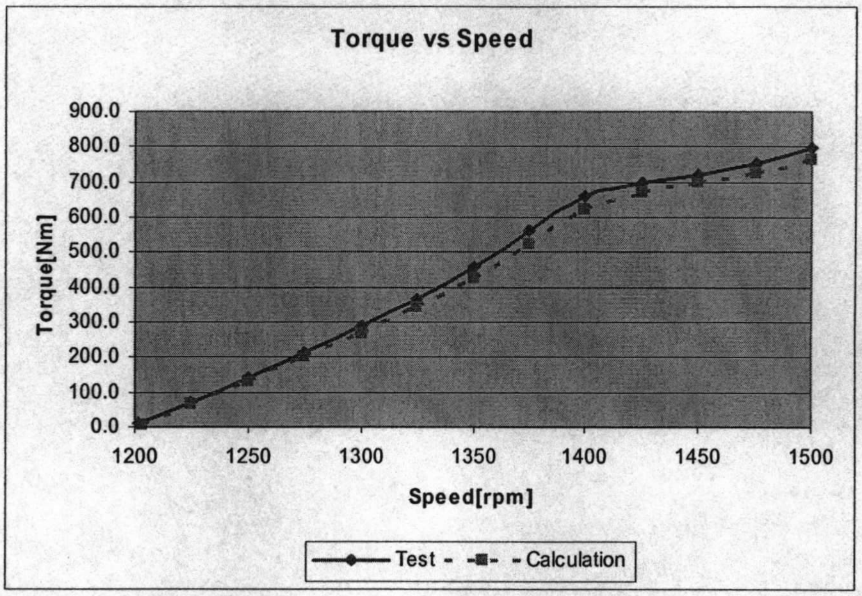


FIGURE 4.9: Torque Comparison between Simulation and Test of 80kW-WRIG with R&L&C

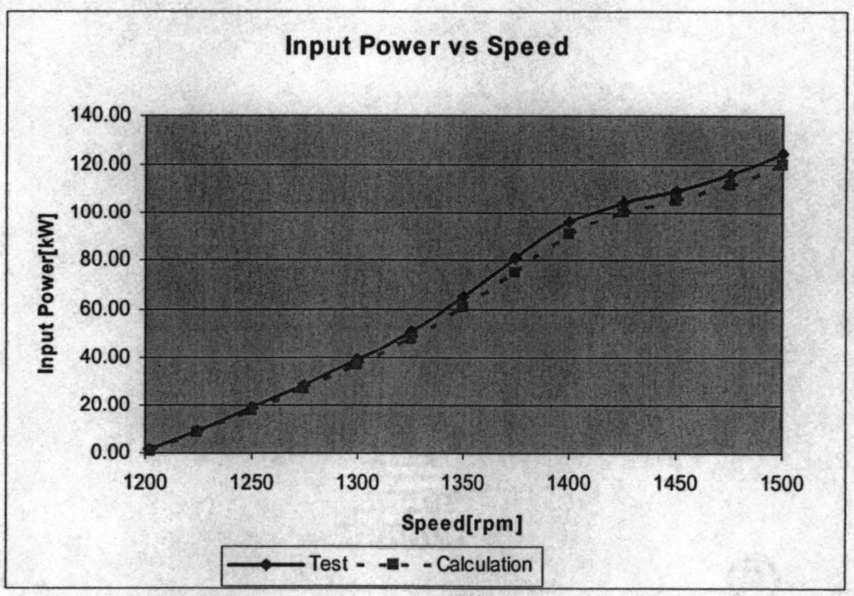


FIGURE 4.10: Input Power Comparison between Simulation and Test of 80kW-WRIG with R&L &C

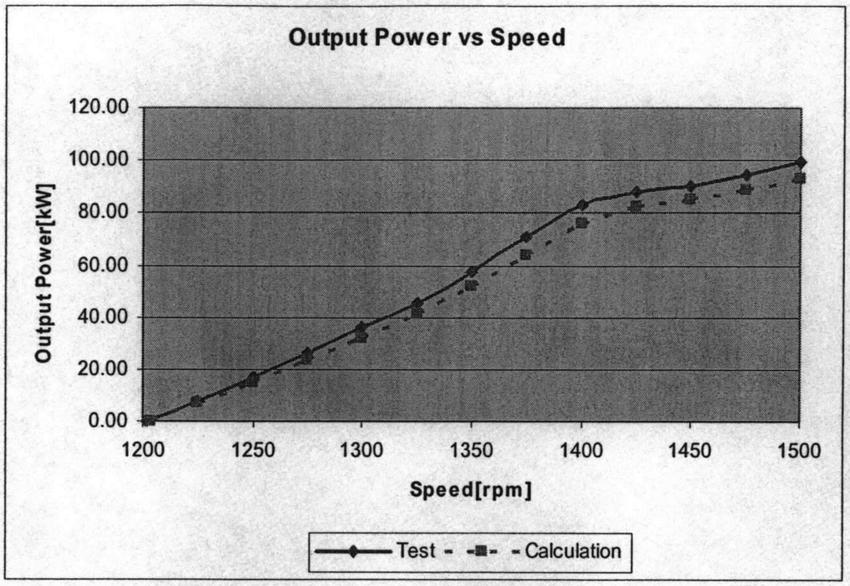


FIGURE 4.11: Output Power Comparison between Simulation and Test of 80kW-WRIG with R&L&C

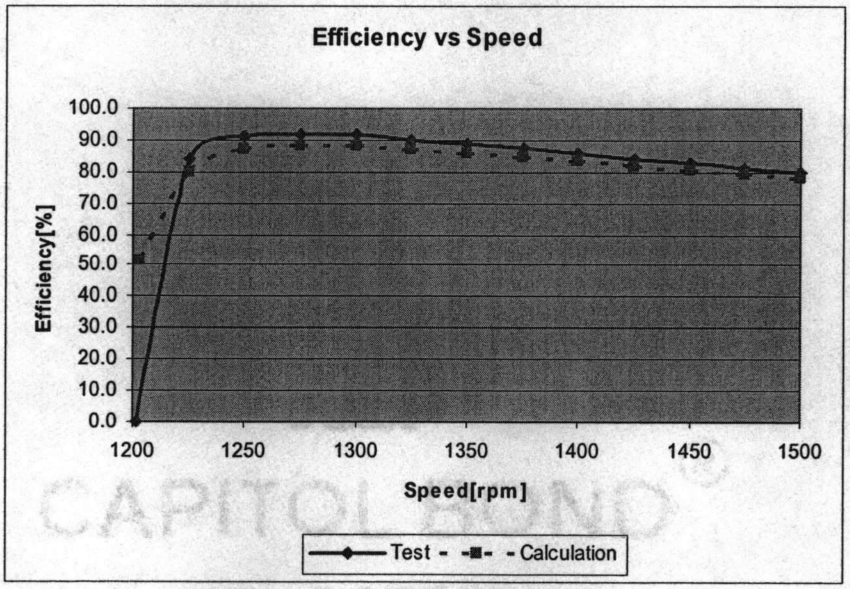


FIGURE 4.12: Efficiency Comparison between Simulation and Test of 80kW-WRIG with R&L&C

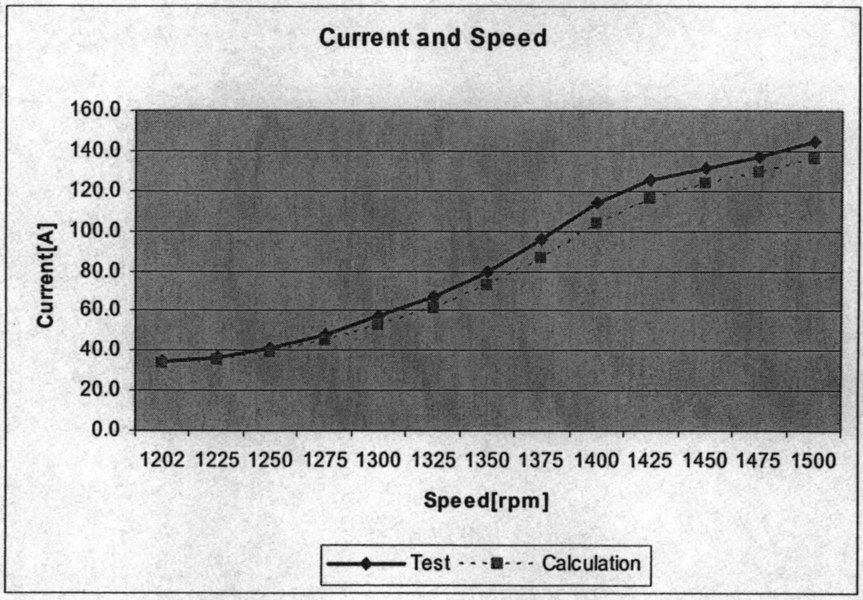


FIGURE 4.13: Stator Current Comparison between Simulation and Test of 80kW-WRIG with R&L&C

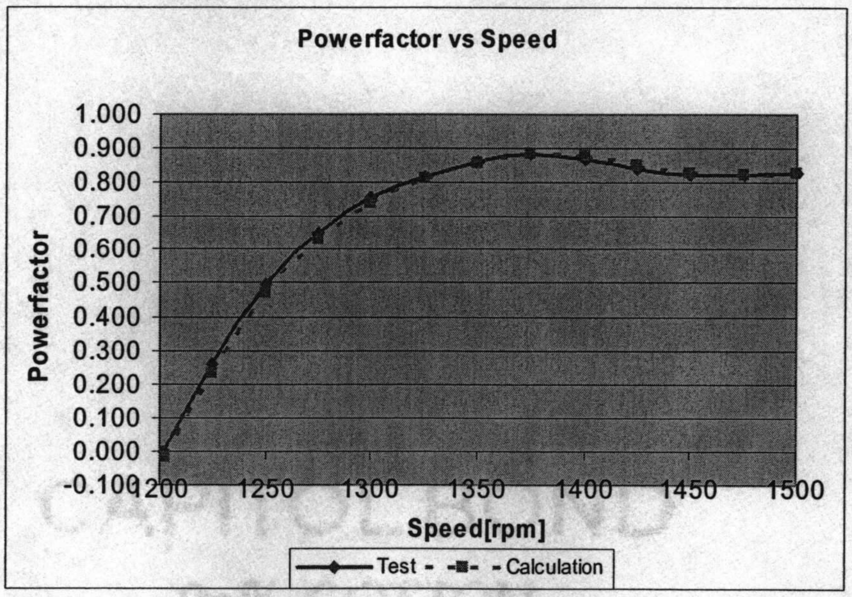


FIGURE 4.14: Power Factor Comparison between Simulation and Test of 80kW-WRIG with R&L&C

Test results show almost same result as that of simulation characteristics as well as external R and L. As expected, the graphs of input and output powers increased steeply at initial points but leveled off somewhat above 1400rpm because of the resonance between L and C in the external rotor circuit.

# 5. Efficiency and Power Factor observation by Simulation

In this section, efficiency and power factor for shorted-rotor, rotor with R&L and with R&L&C WRIG are compared. Since the result of efficiency and power factor by simulation is almost equal to that of test shown as section 4.4, let us use simulation result as appropriate values to compare efficiency and power factor among three conditions of WRIG. As seen in previous result, they have different characteristics in terms of most of their data. Apart from shorted-rotor WRIG, with R&L&C-rotor WRIG's input power slope is not constant since the graph was purposely designed to fit with wind-turbine power characteristic.

In the following sections, efficiency and power factor is utilized to compare among each case by defining x-axis as output power per unit.

## 5.1: Efficiency versus Output Power per Unit

The relationship for shorted-rotor WRIG, with R&L&C-rotor WRIG is shown in FIGURE 5.1. Obviously, shorted-rotor WRIG's speed range to generate acceptably is smaller. Since the shorted-rotor WRIG shows the lowest slip for these conditions to supply 80kW, it is obvious that it will have the highest efficiency. This is clearly shown. The relation can be estimated from Equation 3.9. However, the relation between with R&L and with R&L&C WRIG is not simple because the graph with R&L&C-rotor is not linear. Let us analyze these data referring to Table5.1. If we choose and arbitrary operation at 0.9 p.u, that is equivalent to 72kW output power, to compare each different case, the different operating slip affects the different input power requirements which in turn lead to relative efficiency.

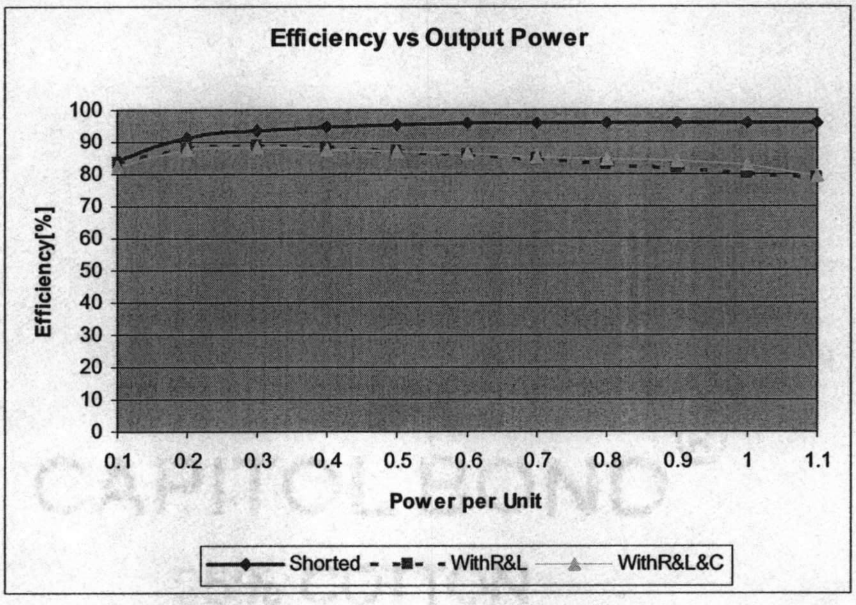


FIGURE 5.1: Efficiency Comparison among Three Different Conditions of 80kW-WRIG with R&L &C

| | Shorted-rotor | With R&L-rotor | With R&L&C-rotor |
|---|---|---|---|
| Output power[kW] | 72.00 | 72.00 | 72.00 |
| Input power[kW] | 75.11 | 88.22 | 85.87 |
| Stator Current[A] | 100.84 | 101.82 | 97.71 |
| Referred Rotor Current [A] | 93.46 | 93.85 | 92.37 |
| Slip | -0.014 | -0.191 | -0.159 |
| Efficiency[%] | 95.881 | 81.61 | 83.85 |
| Whole Z Real[Ω] | 2.36 | 2.32 | 2.514 |
| Whole Z Imaginary[Ω] | 1.40 | 1.43 | 1.31 |
| Power Factor | 0.859 | 0.851 | 0.886 |

TABLE 5.1: Simulation Comparison of 80kW-WRIG at 0.9 p.u. Output Power

## 5.2: Power Factor versus Output Power Unit Observation

With R&L&C-rotor WRIG shows the highest power factor until almost 100% load for three conditions. The real impedance ratio for total impedance has an effect on the power factor which is determined as Equation 3.10. As expected in TABLE 5.1, the real impedance ratio of the R&L&C-connected rotor WRIG is the highest. That means it is expected to get the highest power factor at 0.9 p.u. However, the power factor starts decreasing after 90% load. One of the possible reasons is that a resonance caused by external L& R is passed, then the ratio of real and imaginary impedance starts reducing as well.

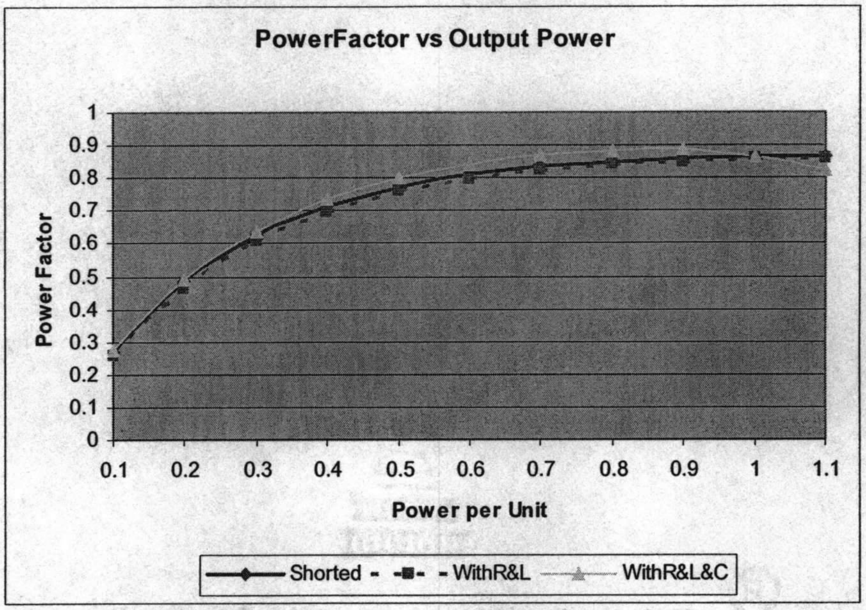


FIGURE 5.2: Power Factor Comparison Among Three Different Conditions of 80kW-WRIG with R&L &C

# 6. Application Model

It was demonstrated that 80kW-WRIG was controlled adding external impedances to adapt it to the characteristics of simulation. In this section, another lower rated WRIG is considered to be connected on the same shaft as that of 80kW-WRIG, indicated in FIGURE 6.1. Therefore, it can spin synchronously with 80kW-WRIG rotor. The applied-WRIG will be designed to fill the lower speed range as implied in FIGURE 6.2. Initial conditions are presumed and simulated to meet this range.

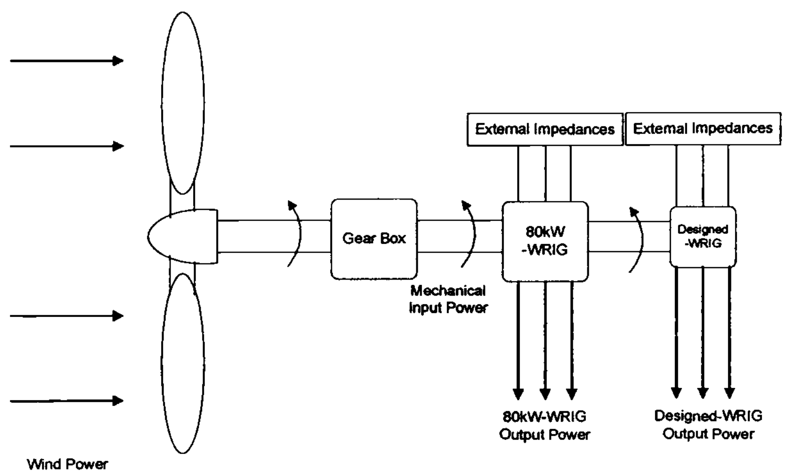


FIGURE 6.1: Configuration of Wind-Turbine and WRIG Configuration

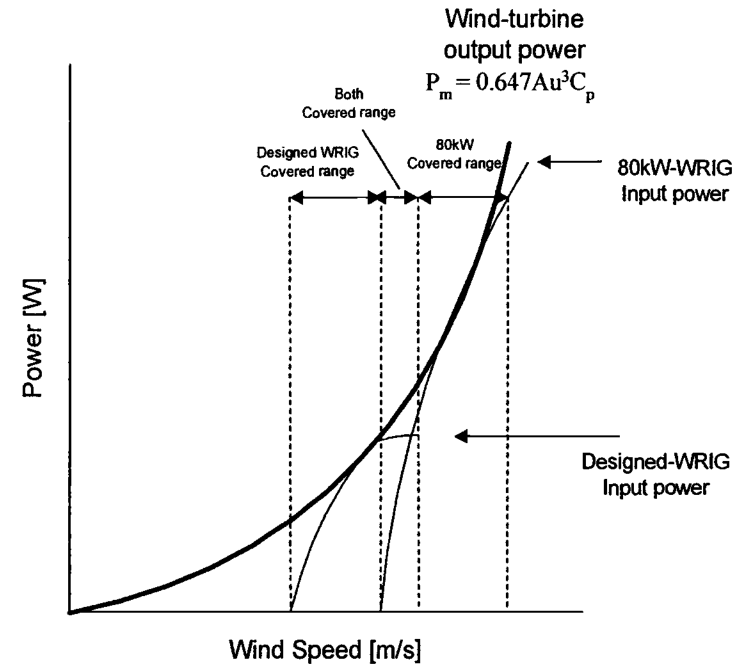


FIGURE 6.2: Designed-WRIG

## 6.1: Applied WRIG Considerations

At the beginning of generating from the 80kW-WRIG, wind speed shows 8.20m/s (1200rpm shaft speed). Up to that speed, the next small WRIG should compensate at lower range using an 8-pole machine. As synchronous rotor speed for this smaller machine is 900rpm, this is equivalent to 6.15m/s wind speed. The WRIG applied needs to cover the lower range. That is 6.15~8.20m/s wind speed range. These two WRIG should both be operating for this intermediate speed over 8.20m/s (1200rpm shaft speed) until 80kW-WRIG power increases enough. Thus, applied small WRIG's output power is reasonably constant after 8.2m/s shown as FIGURE 6.2.

If these WRIG are combined, it would be possible to deal with generating for 6.15~10.25m/s wind speed. The specification of the applied WRIG is determined as follows.

In Fig 3.8, the wind-turbine output power at 8.2m/s (1200rpm shaft speed) is approximately 64kW. In order to design an appropriate WRIG to fit it, we set maximum input power of applied WRIG as 64 kW. Let us use the data of 80kW-WRIG to presume the specification of applied WRIG. Efficiency of WRIG at 115 % load with external R&L&C is 79.8% from the test data in TABLE 4.3. Therefore, the output power at 115% load is evaluated as 51kW. Hereby, the applied WRIG's output power is assumed as 44kW at 100% load. It needs to be designed that the 44kW machine reaches its maximum power at a generator speed of 1200 rpm, where the 80kW machine begins generation. As the speed increases, the output of the smaller machine must be held constant. Next, equivalent circuit parameters to calculate the whole system will be determined as follows.

## 6.2: Estimation of Appropriate External Components Values to Regulate Output Power

From previous section, we presume the rated output power of designed smaller generator is 44kW. Let us neglect output service factor about this designed generator. Since the 100% output power is presumed as 44kW, the output power will be as expressed in Equation 3.11. The data of winding ratio, efficiency, power factor, winding ratio, slip and voltage across rotor of the applied WRIG at 100% loads used are same values as that of 80kW-WRIG with shorted-rotor circuit. Therefore, the applied WRIG can be considered actual WRIG that it has similar characteristic as 80kW-WRIG. The parameters of applied WRIG are shown as TABLE 6.1 by putting these values into Equation 3.3 to 3.11 neglecting external impedances.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| a | 2.486 | $X_1$ | 0.5124[ Ω ] |
| $R_1$ | 0.0397[ Ω ] | $X_2$' | 0.5124[ Ω ] |
| $R_2$' | 0.0727[ Ω ] | $L_2$ | $8.400 \times 10^{-3}$[H] |
| $R_c$ | 259.69[ Ω ] | $X_m$ | 10.56[ Ω ] |

TABLE 6.1: Designed Parameters of 44kW-WRIG

These are applied into Excel and Mat Lab files, then the whole parameters of designed WRIG are manipulated adding external impedances to obtain ideal characteristic such as FIGURE 6.1. After choosing various values, the parameters in TABLE 6.2 were selected.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $R_{ex}$ | 23.00 [ Ω ] | $L_{ex}$ | 0.086[H] |
| $R_{ex}$' | 3.722 [ Ω ] | $X_{Lex}$' | 5.246[ Ω ] |
| $C_{ex}$ | 960[ μ F] | $R_{Lex}$ | 11.500[ Ω ] |
| $X_{cex}$' | 0.447 [ Ω ] | $R_{Lex}$' | 1.861[ Ω ] |

TABLE 6.2: Designed-WRIG Parameters of External R&L&C

Designed WRIG graphs are shown as follows,

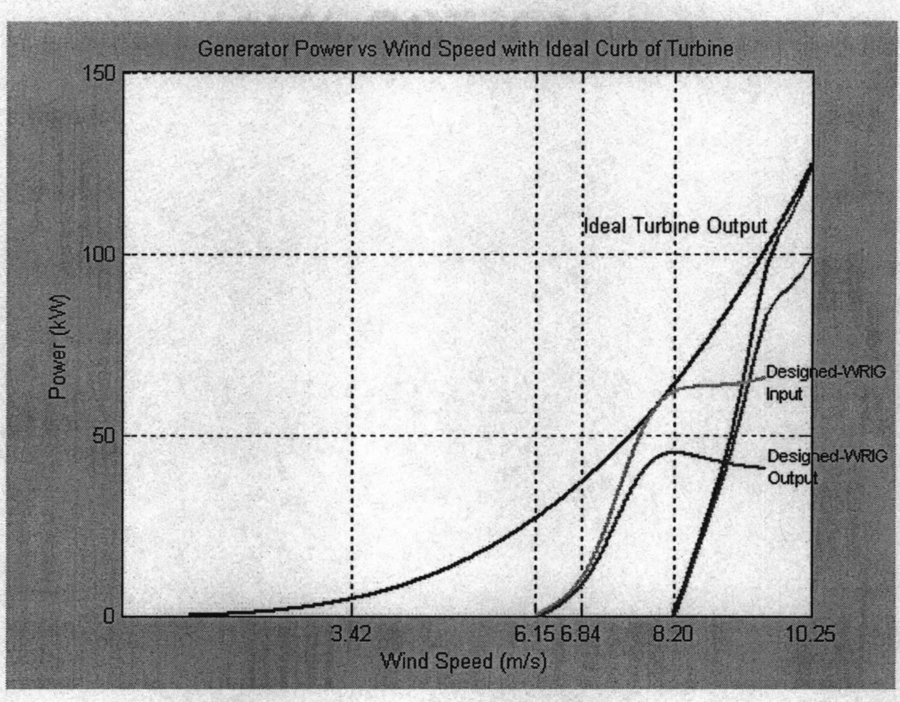


FIGURE 6.3: Designed-WRIG of 44kW Power with Turbine based on Calculation

It is observed that the designed WRIG covers lower range of 80kW-WRIG covered area. Also designed WRIG can generate over 1200rpm range to compensate the lack of output power until 80kW-WRIG increases enough. Naturally, the range can be made even wider by combining additional 4 poles-WRIG and 10 poles-WRIG, as well.

# 7. Conclusions and Recommended Future Work

## 7.1: Conclusions

From previous observations, it was shown that the WRIG was controlled by external impedances passively and optimally. With respect to 80kW-WRIG, we can take advantage of resonance relationship between external inductance and capacitance to approach its input requirement characteristic to the output of a wind-turbine. After building some models of 80kW-WRIG with external impedances in software, it was demonstrated by practical test which configured 80kW-WRIG with mounting external impedances to rotor circuit. Hereby, it was proved to be controllable to design almost any required characteristics of WRIG. We started to design for ideal wind-turbine to fit 80kW-WRIG. Though a wind-turbine was designed for 80kW-WRIG characteristic in this project, it would be designed to suit WRIG to wind turbine characteristic including passively controlled external impedances. Furthermore, it was observed that external R&L&C elements slightly improved power factor of 80kW-WRIG at the same power per unit compared with both R&L and shorted-rotor circuit condition.

A lower power WRIG was designed to compensate lower range of 80kW-WRIG in a tandem connection. Characteristics for this second WRIG were designed to be ideal since input and output power of the designed WRIG were needed to suppress output at over wind speed 8.20m/s (shaft speed 1200rpm). Chosen external impedances obviously contributed to keep input and output power of WRIG constant. Thus, it is applicable that the external impedances are chosen to optimize wind turbine output power characteristic for 6.15~10.25m/s in wind speed range for tandem connected WRIG. The system could develop the extension for further acceptable wind speed by combining multiple WRIGs.

Passively controlled WRIG to handle variable speed generating system was demonstrated in this project. External impedances contributed to the change of power vs. speed characteristics of WRIG. It is considered a simple, economical and reliable method compared to other ways such as power electronics and a mechanical control system, as discussed in first section. However, the switching system of tandem WRIG by wind speed should be considered more in terms of economics. One of the possible advantages of passively controlled system is its simplicity and more saving than wound-rotor doubly-fed machine system, which is practically used, as shown in FIGURE 1.5 with respect to medium and small WRIG because the expense of PE devices raises the whole cost for small and medium WRIG.

Like most natural energy resources, the wind, is variable in speed and unpredictable in magnitude. Thus, our mission is to efficiently harness variable speed wind to be extracted to generate consistently. This project could be one of the biggest steps to design and control WRIG efficiently to enable variable wind speed economically in certain applications.

7.2: Recommended Future Work

In this project, one example was introduced to prove how efficiency and power factor were changed by mounting external impedances with rotor circuit of a WRIG. Viewed from various perspectives, it would be concluded the effect of external impedances are shown.

Practically, connecting these impedances to the rotor circuit outside of WRIG is less effective because it needs more space and maintenance. Therefore, if these impedances are directly mounted to the shaft and controllable, it could be effective and the slip-rings also can be removed.

This project was performed based on steady-state conditions. It is also required to observe how dynamic operation is changed by these external impedances. Hereby, it might be analyzed what is happening to WRIG with external impedances.

Future projects, therefore, should include

1. Dynamic studies of R-L-C control
2. Replacement of slip-ring
3. Switching controls for tandem connected WRIGs.

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# APPENDICES

## APPENDIX A: 80kW-WRIG and Rotor-connected Impedances

1) 80kW-WRIG

| | |
|---|---|
| Name: | Wound Rotor Induction Generator |
| Manufacturer: | Reliance DE MEXICO, S.A. |
| Power: | 80kW |
| Insulation: | H |
| Service Factor: | 1.15 |
| Rated Speed: | 1212rpm |
| Rated Voltage: | 480V |
| Rated Current: | 114A |
| Frequency: | 60Hz |
| Serial number: | B2096201211 |

(The following parameters were computed based on blocked rotor, no load test etc)

| | |
|---|---|
| Rotor-Stator Ratio: | 2.486 |
| $R_1$: | 0.022Ω |
| $X_1$: | 0.12Ω |
| $R_c$: | 149.98Ω |
| $X_m$: | 7.89Ω |
| $R_2$': | 0.0386Ω |
| $X_2$': | 0.2842Ω |

2) Resistor (Rex) for rotor-connected

Name: Resistor

R: 1.078 - 1.252 - 1.883 - 1.891Ω

3) Resistor ($R_{Lex}$) for rotor-connected

Name: Adjustable Resistor

Manufacturer: POWER OHM

Power: 2100W

R: 7~14Ω

Serial number: 2SXR7-7-B2

4) Capacitor ($C_{ex}$) for rotor-circuit

Name: AC RUN Capacitor

Manufacturer: General Electric

C: 50uF

Rated Voltage: 370V AC

Serial number: POC50

5) Inductor (Lex) for rotor connecter

Name: Inductor

L: 137.4 - 229.8 - 296.5 - 368.7 - 441.2mH

$R_L$: 0.385 - 0.451 - 0.506 - 0.572 - 0.638Ω

APPENDIX B: Motor System Resource Facility (MSRF)

1) Dynamometer (Dyno) Control System

Dynamometer

| | |
|---|---|
| Manufacturer: | Marathon Electric Co., Wausau, WI |
| Model: | 1K447THDN4038 AA-W |
| Type: | Wound-Rotor Induction Machine |
| Power: | 300HP |
| Rated Voltage: | 460V |
| Rated Current: | 332A |
| Speed: | 0~4000rpm |
| Poles: | 4 |
| Serial number: | 41890480-9/16 |

Converter

| | |
|---|---|
| Manufacturer: | Kenetech Windpower, Livemore, CA |
| Model: | MD-300 |
| Power: | 300HP |
| Rated Voltage: | 480V |
| Rated Current: | 350A |
| Frequency: | 0~135Hz |
| Serial number: | 001 |

2) Measurement

Torque/Speed Measurement

| | |
|---|---|
| Manufacturer: | Eaton Corp. – Lebow Products |
| Model: | 1805-10K Torque Sensor, 7540 Signal Conditioner |
| Torque Rating: | 10,000LB-in |
| Speed range: | 0~22,000 rpm |
| Serial number: | 532 |

Power Analyzer

| | |
|---|---|
| Manufacturer: | Voltech |
| Model: | PM 3300 Power Analyzer |
| Serial number: | AJ10/9463 |

AC Voltage Meter

| | |
|---|---|
| Manufacturer: | FLUKE |
| Model: | 179 TRUE RMS MULTIMETER |
| Measured range: | 0~600V |

AC Current Meter

| | |
|---|---|
| Manufacturer: | FLUKE |
| Model: | FLUKE 36 |
| Measured range: | 0~600A |

Ohm Meter

| | |
|---|---|
| Manufacturer: | NGI |
| Model: | DIGITAL MICROHMMETER-D3700 |
| Measured range: | 0~60Ω |

LCR METER

| | |
|---|---|
| Manufacturer: | HEWLETT PACKARD |
| Model: | PRECISION LCR METER |
| Frequency range: | 20Hz~1MHz |
| Serial number: | 4284A. |

# APPENDIX C: Simulation result

Excel and MATLAB simulation data are included in this section.

1) 80kW-WRIG Excel sheet with external rotor R&L

| Synchronous speed | | | 1200 | rpm | 125.6 | rad/s | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | | | | | | | | | | | | |
| N[rpm] | 1201 | 1225 | 1250 | 1275 | 1300 | 1325 | 1350 | 1375 | 1400 | 1425 | 1450 | 1475 | 1500 |
| w[rad/s] | 125 | 128.28 | 130.90 | 133.51375 | 136.13167 | 138.74958 | 141.3675 | 143.98542 | 146.60333 | 149.22125 | 151.83917 | 154.45708 | 157.075 |
| R1 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| X1 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| R2' | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| X2' | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Rm | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 | 149.98 |
| Xm | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 | 7.89 |
| V | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 | 277.13 |
| a | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 | 2.49 |
| s | 0.00 | -0.02 | -0.04 | -0.06 | -0.08 | -0.10 | -0.13 | -0.15 | -0.17 | -0.19 | -0.21 | -0.23 | -0.25 |
| R_L | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 |
| Rex | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 | 3.11 |
| Lex | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| R_L' | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Rex' | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| XL' | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 | 24.34 |
| (R and L) | | | | | | | | | | | | | |
| R2'/s | -46.32 | -1.85 | -0.93 | -0.62 | -0.46 | -0.37 | -0.31 | -0.26 | -0.23 | -0.21 | -0.19 | -0.17 | -0.15 |
| A | -145.50 | -13.78 | -9.96 | -7.34 | -5.68 | -4.57 | -3.79 | -3.22 | -2.78 | -2.44 | -2.16 | -1.93 | -1.74 |
| B | 11.49 | 10.11 | 9.02 | 8.61 | 8.42 | 8.33 | 8.28 | 8.25 | 8.23 | 8.21 | 8.20 | 8.19 | 8.19 |
| C | -88.88 | -23.47 | -13.37 | -9.00 | -6.88 | -5.70 | -4.97 | -4.48 | -4.13 | -3.87 | -3.67 | -3.51 | -3.38 |
| D | -1146.75 | -110.78 | -81.15 | -60.74 | -47.72 | -39.05 | -32.94 | -28.45 | -25.01 | -22.30 | -20.11 | -18.31 | -16.80 |
| Zm(real) | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Zm(imag) | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 |
| Z3(real) | -99.59 | -12.34 | -9.45 | -7.14 | -5.63 | -4.62 | -3.90 | -3.37 | -2.96 | -2.65 | -2.39 | -2.17 | -2.00 |
| Z3(imag) | 3.33 | 1.95 | 0.87 | 0.45 | 0.27 | 0.18 | 0.13 | 0.09 | 0.07 | 0.06 | 0.05 | 0.04 | 0.03 |
| Z2(real) | -145.91 | -14.20 | -10.37 | -7.76 | -6.09 | -4.99 | -4.21 | -3.63 | -3.20 | -2.85 | -2.57 | -2.34 | -2.15 |
| Z2(ima) | 3.62 | 2.24 | 1.15 | 0.74 | 0.55 | 0.46 | 0.41 | 0.38 | 0.36 | 0.34 | 0.33 | 0.32 | 0.32 |
| Z2 | 145.96 | 14.37 | 10.44 | 7.79 | 6.12 | 5.01 | 4.23 | 3.65 | 3.22 | 2.87 | 2.59 | 2.37 | 2.17 |
| Z1(real) | 0.01 | -2.70 | -3.30 | -3.55 | -3.49 | -3.29 | -3.04 | -2.79 | -2.55 | -2.35 | -2.16 | -2.00 | -1.86 |
| Z1(imag) | 8.16 | 6.32 | 5.43 | 4.38 | 3.47 | 2.79 | 2.29 | 1.92 | 1.66 | 1.46 | 1.31 | 1.19 | 1.10 |
| Z1 | 8.16 | 6.88 | 6.35 | 5.63 | 4.93 | 4.31 | 3.80 | 3.39 | 3.04 | 2.76 | 2.53 | 2.33 | 2.16 |
| I1(real) | -0.04 | 15.84 | 22.65 | 30.98 | 39.91 | 49.04 | 58.22 | 67.34 | 76.36 | 85.23 | 93.92 | 102.41 | 110.66 |
| I1(imag) | 33.94 | 37.05 | 37.31 | 38.23 | 39.66 | 41.53 | 43.81 | 46.49 | 49.55 | 52.96 | 56.76 | 60.87 | 65.30 |
| I1 | 33.94 | 40.29 | 43.65 | 49.21 | 56.26 | 64.26 | 72.86 | 81.63 | 91.03 | 100.36 | 109.74 | 119.13 | 128.49 |
| PF(cosI1) | 0.00 | 0.39 | 0.52 | 0.63 | 0.71 | 0.76 | 0.80 | 0.82 | 0.84 | 0.85 | 0.86 | 0.86 | 0.86 |
| V2(real) | 267.48 | 266.95 | 267.02 | 266.94 | 266.74 | 266.41 | 265.96 | 265.40 | 264.73 | 263.95 | 263.06 | 262.06 | 261.00 |
| V2(imag) | 0.73 | 5.32 | 7.26 | 9.65 | 12.21 | 14.85 | 17.51 | 20.16 | 22.79 | 25.39 | 27.94 | 30.44 | 32.89 |
| V2 | 267.48 | 267.00 | 267.12 | 267.12 | 267.01 | 266.82 | 266.53 | 266.16 | 265.71 | 265.16 | 264.54 | 263.84 | 263.07 |
| I2'(real) | 1.83 | 18.35 | 25.44 | 34.13 | 43.46 | 53.06 | 62.75 | 72.45 | 82.10 | 91.68 | 101.16 | 110.51 | 119.71 |
| I2'(imag) | 0.05 | 2.89 | 2.83 | 3.24 | 3.95 | 4.92 | 6.11 | 7.52 | 9.15 | 10.97 | 13.00 | 15.21 | 17.62 |
| I2' | 1.83 | 18.58 | 25.59 | 34.28 | 43.64 | 53.29 | 63.04 | 72.84 | 82.61 | 92.34 | 101.99 | 111.55 | 121.00 |
| Torque | 11.77 | 116.99 | 162.22 | 217.62 | 277.06 | 337.98 | 399.28 | 460.35 | 520.82 | 580.40 | 638.86 | 696.08 | 751.83 |
| Pm[kW] | 1.47 | 15.01 | 21.23 | 29.06 | 37.72 | 46.89 | 56.45 | 66.28 | 76.35 | 86.61 | 97.01 | 107.51 | 118.09 |
| Pe[kW] | -0.04 | 13.17 | 18.83 | 25.76 | 33.18 | 40.77 | 48.40 | 55.99 | 63.49 | 70.86 | 78.09 | 85.14 | 92.00 |
| Eff(%) | 2.52 | 87.74 | 88.69 | 88.66 | 87.97 | 86.95 | 85.75 | 84.47 | 63.15 | 81.82 | 80.50 | 79.19 | 77.91 |

## 2) 80kW-WRIG Excel sheet with external rotor R&L&C

| Synchronous speed | | | 1200 | rpm | 125.7 | rad/s | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | | | | | | | | | | | | |
| N[rpm] | 1203 | 1225 | 1250 | 1275 | 1300 | 1325 | 1350 | 1375 | 1400 | 1425 | 1450 | 1475 | 1500 |
| w[rad/s] | 126.0 | 128.3 | 130.9 | 133.5 | 136.1 | 138.8 | 141.4 | 144.0 | 146.6 | 149.2 | 151.8 | 154.5 | 157.1 |
| R1 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| X1 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| R2' | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| X2' | 0.28 | 0.28 | 0.26 | 0.28 | 0.26 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.26 | 0.28 | 0.28 |
| Rm | 149.98 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 | 150.0 |
| Xm | 7.89 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 |
| V | 277.13 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 | 277.1 |
| a | 2.49 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| s | 0.00 | -0.02 | -0.04 | -0.06 | -0.08 | -0.10 | -0.13 | -0.15 | -0.17 | -0.19 | -0.21 | -0.23 | -0.25 |
| R_L | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| Rex | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| Lex | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 |
| R_L' | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 | 2.27 |
| Rex' | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| X_L' | 26.90 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 | 26.9 |
| C | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 |
| | | | | | | | | | | | | | |
| X_C' Wye | 137346.2168 | 1977.7855 | 494.4 | 219.8 | 123.6 | 79.1 | 54.9 | 40.4 | 30.9 | 24.4 | 19.8 | 16.3 | 13.7 |
| (R&L&C) | | | | | | | | | | | | | |
| R2'/s | -15.44 | -1.85 | -0.93 | -0.62 | -0.46 | -0.37 | -0.31 | -0.26 | -0.23 | -0.21 | -0.19 | -0.17 | -0.15 |
| A | -215.66 | -25.50 | -12.51 | -6.16 | -5.95 | -4.59 | -3.63 | -2.88 | -2.31 | -2.00 | -1.84 | -1.72 | -1.60 |
| B | 7.66 | 7.86 | 7.85 | 7.84 | 7.82 | 7.80 | 7.80 | 7.88 | 8.03 | 8.23 | 8.34 | 8.35 | 8.33 |
| C | -89.40 | -10.84 | -5.20 | -3.29 | -2.24 | -1.53 | -1.13 | -1.28 | -2.39 | -3.88 | -4.60 | -4.67 | -4.48 |
| D | -1700.4 | -203.9 | -101.7 | -67.5 | -50.1 | -39.4 | -31.8 | -25.9 | -21.4 | -18.8 | -17.5 | -16.6 | -15.6 |
| Zm(real) | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Zm(Imag) | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 | 7.87 |
| Z3(real) | -200.64 | -24.06 | -12.00 | -7.95 | -5.90 | -4.84 | -3.73 | -3.02 | -2.49 | -2.20 | -2.07 | -1.96 | -1.66 |
| Z3(Imag) | -0.29 | -0.30 | -0.30 | -0.32 | -0.34 | -0.35 | -0.35 | -0.29 | -0.12 | 0.08 | 0.18 | 0.20 | 0.18 |
| Z2(real) | -216.1 | -25.9 | -12.9 | -6.6 | -6.4 | -5.0 | -4.0 | -3.3 | -2.7 | -2.4 | -2.3 | -2.1 | -2.0 |
| Z2(Ima) | 0.0 | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 | -0.1 | 0.0 | 0.2 | 0.4 | 0.5 | 0.5 | 0.5 |
| Z2 | 216.1 | 25.9 | 12.9 | 8.6 | 6.4 | 5.0 | 4.0 | 3.3 | 2.7 | 2.4 | 2.3 | 2.2 | 2.1 |
| Z1(real) | 0.1 | -1.8 | -3.3 | -3.9 | -3.9 | -3.6 | -3.3 | -2.8 | -2.4 | -2.0 | -1.9 | -1.8 | -1.7 |
| Z1(Imag) | 8.2 | 7.7 | 6.3 | 4.8 | 3.6 | 2.6 | 2.0 | 1.5 | 1.3 | 1.2 | 1.3 | 1.2 | 1.1 |
| Z1 | 8.2 | 7.9 | 7.1 | 6.2 | 5.3 | 4.5 | 3.8 | 3.2 | 2.7 | 2.4 | 2.3 | 2.1 | 2.0 |
| I1(real) | -0.6 | 8.2 | 18.2 | 28.4 | 38.8 | 49.9 | 62.2 | 76.6 | 91.2 | 99.0 | 102.3 | 106.5 | 112.2 |
| I1(imag) | 33.9 | 34.0 | 34.3 | 34.8 | 35.4 | 36.1 | 37.3 | 40.4 | 49.0 | 61.0 | 68.6 | 72.8 | 76.4 |
| I1 | 33.9 | 35.0 | 38.8 | 44.9 | 52.5 | 61.6 | 72.5 | 86.6 | 103.5 | 116.3 | 123.2 | 129.0 | 135.7 |
| PF(cosI1) | 0.0 | 0.2 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 |
| V2(real) | 267.5 | 267.6 | 267.8 | 267.9 | 267.9 | 268.0 | 267.9 | 267.3 | 265.2 | 262.0 | 259.9 | 258.8 | 257.9 |
| V2(imag) | 0.6 | 3.1 | 5.9 | 8.8 | 11.8 | 15.0 | 18.5 | 22.7 | 27.0 | 29.5 | 30.6 | 31.9 | 33.6 |
| V2 | 267.5 | 267.7 | 267.8 | 268.0 | 268.2 | 268.4 | 268.5 | 268.3 | 266.6 | 263.6 | 261.7 | 260.7 | 260.1 |
| I2'(real) | 1.2 | 10.3 | 20.7 | 31.3 | 42.1 | 53.6 | 66.4 | 81.6 | 97.5 | 107.0 | 111.3 | 116.4 | 122.8 |
| I2'(imag) | 0.0 | 0.0 | 0.0 | -0.1 | -0.3 | -0.7 | -1.1 | -0.2 | 5.7 | 16.1 | 23.0 | 26.2 | 28.3 |
| I2' | 1.2 | 10.3 | 20.7 | 31.3 | 42.1 | 53.6 | 66.4 | 81.6 | 97.6 | 108.2 | 113.7 | 119.3 | 126.1 |
| Torque | 7.9 | 66.0 | 132.5 | 200.1 | 269.6 | 343.4 | 425.8 | 522.4 | 620.3 | 673.3 | 695.5 | 724.2 | 762.7 |
| Pm[kW] | 1.0 | 8.5 | 17.3 | 26.7 | 36.7 | 47.6 | 60.2 | 75.2 | 90.9 | 100.5 | 105.6 | 111.9 | 119.8 |
| Pe[kW] | -0.5 | 6.8 | 15.1 | 23.6 | 32.3 | 41.5 | 51.7 | 63.7 | 75.8 | 82.3 | 85.0 | 88.6 | 93.3 |
| Eff(%) | 51.6 | 80.1 | 87.2 | 88.2 | 87.9 | 87.0 | 85.9 | 84.7 | 83.4 | 81.9 | 80.5 | 79.2 | 77.9 |

3) 80kW-WRIG power with ideal wind turbine MATLAB program

```
a=2.486;                    % Turns ratio
f=60;                       % Stator frequency
Ns=1200;                    % Synchronous speed(Rated speed 1212[rpm])
N=1200.1:0.1:1500;          % 1500rpm designated speed value of generator
s=(Ns-N)/Ns;                % Slip
f_s=f*s;                    % Rotor frequency
w=(1-s)*Ns*2*pi/60;         % Actual rotor speed
Rm=466;                     % WRIG parameters as below
Xm=7.871;
R1=0.022;
X1=0.2842;
R2_r=0.0385;                % Rotor leakage resistance(R2')referred to stator
X2_r=0.2842;                % Rotor leakage reactance(X2')referred to stator
%1-----------------------Testing Data of Generator Input power---------------------------%
N=[1200 1202 1225 1250 1275 1300 1325 1350 1375 1400 1425 1450 1475 1500];
Pe=[0 1.65 9.44 18.81 28.48 39.12 50.78 64.75 81.06 96.76 104.45 109.43 116.00
124.87];
plot(N,Pe,'b','LineWidth',1.5);
grid on;
hold on
```

```
xlabel('Speed (rpm)');

ylabel('Pe (kW)');

%2----------------------Testing Data of Generator Output power------------------------%

N=[1200 1202 1225 1250 1275 1300 1325 1350 1375 1400 1425 1450 1475 1500];

Pe=[0 0 7.91 17.12 26.19 35.98 45.75 57.52 70.89 82.98 87.91 90.37 94.17 99.62];

plot(N,Pe,'r','LineWidth',1.5);

grid on;

hold on

xlabel('Speed (rpm)');

ylabel('Pe (kW)');

gtext('Ideal Turbine Output')

title 'Generator Power vs Speed with Ideal Curb of Turbine'



%3------------------Wind Turbine Characteristic with R&L&C-------------------------%

clear all

A=512.2;                  % Cross section area [m^2]

p=101.3;                  % The pressure in kilopascal [kpa]

T=273;                    % Temperature in kelvin [K]

ramda=5.190;              % The tip-speed ratio

r_m=13.55;                % The maximum radius of the rotating turbine [m]

u=1:0.01:10.2525;         % Wind Speed range [m/s]
```

```
omega_m=u*ramda/r_m;        % w_m=u*ramda/r_m
N=60*omega_m/(2*pi);        % Speed range [rpm]
a=40;  %25                  % Gear ratio
N_a=N*a;                    % Speed range with gear ratio
C_p=0.35;                   % Coefficient of wind performance
row=3.485*p/T;              % Air density [kg/m^3]
P_w=C_p*1.742*p*A*u.^3/(T*1000);        % The power in the wind
plot(N_a,P_w,'k','LineWidth',1.5)
xlabel('Speed (rpm)');
ylabel('Power (W)');
grid on;
hold off
```

4) Calculation of Designed WRIG

Assuming efficiency 79.8% at 115%-load, p.f. 0.867 at 100%-load,

slip -0.015 at 100%

Input Power: 63.94kW at 115% load from MATLAB simulation

Output Power: 51.02kW at 115% considering 79.8% efficiency at with R&L&C

Output Power: 44.37kW at 100%

Since stator current at 100% load is computed from Equation (3.11)

$$\left|I_1\right| = \frac{44.37\times10^3}{3\times\frac{480}{\sqrt{3}}\times0.867} = 61.56 \text{ [A]}$$

$I_1$= 53.37+31.00j [A]

$$V_2 = \frac{480}{\sqrt{3}} + (53.37+31.00j)(R_1+jX_1) = 263.36+28.58j$$

From the above Equations

$R_1$= 0.0397[Ω], $X_1$=0.5124[Ω]

As it is wound rotor induction machine

$X_2$'=0.5124[Ω]

Input power is derived from Equation (3.9)

$$3\left|I_2\right|^2(1-(-0.015))\frac{R_2'}{-0.015} = 55.6\times10^3$$

Rotor current referred to stator is

$$I_2' = -\frac{263.36+28.58}{\frac{R_2'}{-0.015}+jX_2'}$$

From the above 2 Equations,

$R_2$'=0.0727, $I_2$'=55.06+5.93j

Current going through mutual impedances is

$I_m$ = $I_2$'- $I_1$ = -1.69+25.08j

Mutual impedance is

$$Z_m = \frac{jR_cX_m}{R_c+jX_m} = \frac{V_2}{I_m} = \frac{263.36+29.43j}{-1.69+25.08j} = \text{-0.43-10.54j}$$

From this Equation,

Rc=259.7, Xm= 10.56

Therefore, we could get the parameters of designed-WRIG shown as Table 6.1.

5) 80kW, designed 44.37kW-WRIG with ideal wind turbine MATLAB program

```
N= [1200 1202 1225 1250 1275 1300 1325 1350 1375 1400 1425 1450 1475 1500];
Pe= [0 1.65 9.44 18.81 28.48 39.12 50.78 64.75 81.06 96.76 104.45 109.43 116.00
124.87];
plot(N,Pe,'b','LineWidth',1.5);
grid on;
hold on
xlabel('Speed (rpm)');
ylabel('Pe (kW)');

%1-------------------Testing Data of Generator Output power-----------------------------%
N=[1200 1202 1225 1250 1275 1300 1325 1350 1375 1400 1425 1450 1475 1500];
Pe=[0 0 7.91 17.12 26.19 35.98 45.75 57.52 70.89 82.98 87.91 90.37 94.17 99.62];
plot(N,Pe,'r','LineWidth',1.5);
grid on;
hold on
xlabel('Speed (rpm)');
```

```
ylabel('Pe (kW)');

gtext('Ideal Turbine Output')

axis([0 1500 0 150]);

title 'Generator Power vs Speed with Ideal Curb of Turbine'


%2-------------------------Wind Turbine Characteristic-----------------------------------%

clear all

A=512.2;  %187                    % Cross section area [m^2]

p=101.3;                          % The pressure in kilopascal [kpa]

T=273;                            % Temperature in kelvin [K]

ramda=5.190;  %5.190              % The tip-speed ratio

r_m=13.55;  %8.35                 % The maximum radius of the rotating turbine [m]

u=1:0.01:10.2525;                 % Wind Speed range [m/s]

omega_m=u*ramda/r_m;              % w_m=u*ramda/r_m

N=60*omega_m/(2*pi);              % Speed range [rpm]

a=40;  %25                        % Gear ratio

N_a=N*a;                          % Speed range with gear ratio

C_p=0.35;

row=3.485*p/T;                    % Air density [kg/m^3]

P_w=C_p*1.742*p*A*u.^3/(T*1000); % The power in the wind

plot(N_a,P_w,'k','LineWidth',1.5)

xlabel('Speed (rpm)');
```

```
ylabel('Power (kW)');
grid on;
N_a1=1200;
N1=N_a1/a;
omega_m1=N1*2*pi/60;
u_1=omega_m1*r_m/ramda
P_w1=C_p*1.742*p*A*u_1.^3/(T*1000)
N_a1=900;
N1=N_a1/a;
omega_m1=N1*2*pi/60;
u_1=omega_m1*r_m/ramda
P_w1=C_p*1.742*p*A*u_1.^3/(T*1000)


%3-----------------------------Designed 44.37kW-WRIG -----------------------------------%
a=2.48; %Turns ratio
f=60;
Ns=900;                    % Synchronous speed  and rated speed 911[rpm]
N=900.1:0.1:1400;          % Rotor speed range
s=(Ns-N)/Ns;               % Slip
f_s=f*s; % Rotor frequency % Rotor Frequency
w=(1-s)*Ns*2*pi/60;        % Actual rotor speed
Rm=259.688;                % WRIG parameters below
```

```
Xm=10.560;

R1=0.0397;

X1=0.5124;

R2_r=0.0727;                % Rotor leakage resistance (R2') referred to stator

X2_r=0.5124;                % Rotor leakage reactance (X2') referred to stator


%4-------------------------Designed 44.37kW-WRIG parameters--------------------------%

RL=11.5;                % Resistance of external inductance [ohms]

Rex=23;                 % External resistors [ohms]

L=0.086;                % Inductance of external inductance [H]

C=960*10^(-6);          % Capacitance of external[F]

RL_r=RL./a.^2;          % Resistance of external Inductance referred to stator

Rex_r=Rex./a.^2;        % Resistance of external Resistance referred

Xex_r=2*pi*f_s.*L./(s.*a.^2);        %Reactance of external Inductance

Xc_ry=1./(2*pi*f_s.*s.*C.*a.^2);    %Capacitance with wye connection

V1=480/sqrt(3); % Phase voltage

Zm=Rm.*Xm.*i./(Rm+Xm.*i);

Z3=(RL_r./s+(Xex_r-Xc_ry).*i).*(Rex_r./s)./(RL_r./s+(Xex_r-Xc_ry).*i+Rex_r./s);

Z3_r=real(Z3);

Z3_i=imag(Z3);

Z2_r=R2_r./s+Z3_r;

Z2_i=X2_r+Z3_i;
```

```
Z2=Z2_r+Z2_i.*i;

Zin=R1+X1.*i+Z2.*Zm./(Z2+Zm);

Zin_abs=abs(R1+X1.*i+Z2.*Zm./(Z2+Zm));


I1_r=real(-V1./Zin);

I1_i=imag(-V1./Zin);

I1_c=I1_r+I1_i.*i;

I1=sqrt(I1_r.^2+I1_i.^2);

phi=angle(-V1./Zin);

pf=cos(phi);

Va_r=real(V1+I1_c.*(R1+X1*i));

Va_i=imag(V1+I1_c.*(R1+X1*i));

Va_c=Va_r+Va_i*i;

Va=sqrt(Va_r.^2+Va_i.^2);

I2_r=real(-Va_c./Z2);

I2_i=imag(-Va_c./Z2);

I2=sqrt(I2_r.^2+I2_i.^2);

T=3.*(abs(I2)).^2.*(1-s).*(abs(Z2_r))./w;     %Total torque

Pm=w.*T/1000;

%Pm=3.*(abs(I2)).^2.*(1-s).*(R2_r./s+Z3_r)/1000; %Total input mechanical power

Pe1=3.*abs(V1).*abs(I1).*pf./1000;

P_m1=max(Pm)
```

```
Eff=abs(Pe1./Pm.*100); % Efficiency of Generator

plot(N,Pm,'g','LineWidth',1.5)

%xlabel('Speed (rpm)');

%ylabel('Pe (kW)');

grid on;

plot(N,Pe1,'r','LineWidth',1.5)

grid on;

hold off
```