# LOW FREQUENCY TRANSMISSION FOR REMOTE POWER GENERATING SYSTEMS

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Anupama Keeli

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# LOW FREQUENCY TRANSMISSION FOR REMOTE POWER GENERATING SYSTEMS

Approved by:

Dr. A.P. Sakis Meliopoulos, Advisor
School of Electrical and Computer Engineering
*Georgia Institute of Technology*

Dr. David Taylor
School of Electrical and Computer Engineering
*Georgia Institute of Technology*

Dr. Deepakraj M Divan
School of Electrical and Computer Engineering
*Georgia Institute of Technology*

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| A | Annual investment for cable and converter |
| AC | Alternating Current |
| ACost | Acquisition cost of the cable per feet |
| CCost | Acquisition cost of cable for entire wind farm |
| $Cost_{conv}$ | Cost of converter |
| $Cost_{inv}$ | Cost of inverter |
| $CCost_m$ | Cost of m parallel cables |
| $d_i$ | Distance between adjacent wind turbines in feeder i |
| DC | Direct Current |
| ft | feet |
| HVDC | High Voltage Direct Current |
| Hz | Hertz |
| i | Interest rate |
| $I_{DC}$ | DC current in the DC circuit |
| kV | Kilovolt |
| l | Distance from the last wind turbine to the collection point |
| L | Total length of cable |
| LFAC | Low frequency AC transmission |
| $Loss_m$ | Loss for m parallel cables |
| m | Number of parallel cables |
| $m_i$ | Number of wind turbines in the radial feeder i |

| | |
|---|---|
| MW | Mega Watt |
| n | Life time |
| N | Number of wind turbines |
| $n_f$ | Number of radial feeders |
| P | Acquisition cost of the cable and converter |
| $P_L$ | Transmission power loss |
| $P_t$ | Power rating of the wind turbine |
| r | Resistance of the cable per unit length |
| R | Positive sequence resistance of medium voltage cable per unit length |
| $V_{gn}$ | Nominal generator voltage |
| $V_{xn}$ | Nominal high side transformer voltage |
| WinIGS | Windows Integrated Grounding System |
| WTS | Wind Turbine System |
| X | Positive sequence reactance of medium voltage cable per unit length |

# SUMMARY

The goal of this Masters Thesis research is to evaluate alternative transmission systems from remote wind farms to the main grid using low-frequency AC technology. Low frequency means a frequency lower than nominal frequency (60/50Hz). The low-frequency AC network can be connected to the power grid at major substations via cyclo-converters that provide a low-cost interconnection and synchronization with the main grid. Cyclo-converter technology is utilized to minimize costs which result in systems of 20/16.66 Hz (for 60/50Hz systems respectively). Low frequency transmission has the potential to provide an attractive solution in terms of economics and technical merits.

The optimal voltage level selection for transmission within the wind farm and up to the interconnection with the power grid is investigated. The proposed system is expected to have costs substantially lower than HVDC and conventional HVAC systems. The cost savings will come from the fact that cyclo-converters are used which are much lower in cost than HVDC. Other savings can come from optimizing the topology of the wind farms. Another advantage of the proposed topologies is that existing transformers designed for 60 Hz can be used for the proposed topologies (for example a 345kV/69 kV, 60Hz transformer can be used for a 115 kV/23kV, 20 Hz system).

The results from this research indicate that the use of LFAC technology for transmission reduces the transmission power losses and the cost of the transmission system. The alternate topologies suitable for various geographical locations and optimal voltage for transmission within the wind farms are presented in the thesis.

# CHAPTER 1

# INTRODUCTION

## 1.1 Problem Statement

Renewable sources of energy are widely available and proper utilization of these resources leads to decreased dependence on the fossil fuels. Wind is one such renewable source available in nature and could supply at least a part of the electric power. In many remote locations the potential for wind energy is high. Making use of the available wind resources greatly reduces the dependence on the conventional fuels and lowers the emission rates.

There are a few problems associated with the wind which makes the wind energy more expensive than other forms of electric power generation. The two main issues are: (a) Large wind farms are located in remote locations which make the cost of transmission of wind power costly, and (b) the intermittent supply of power due to the unpredictability of the wind that results in lower capacity credits for the operation of the integrated power system.

These issues are addressed by designing alternative topologies and transmission systems operating at low frequency for the purpose of decreasing the cost of transmission and making the wind farm a more reliable power source. The use of DC transmission within the wind farm enables the output of wind generators to be rectified via a standard transformer/rectifier arrangement to DC of appropriate kV level.

## 1.2 Research Objectives

The following tasks have been carried out for the development of alternate topologies with low frequency transmission technology.

- Literature study of previous research on low frequency AC transmission and wind farm topologies.
- Design of alternate topologies.
- Calculation of optimal transmission voltage levels for different topologies.
- Modeling the system using WinIGS-F software.

Optimization of the system is done depending on the area covered by the wind farm. Storage can be provided at the DC buses. The storage is not unique to low-frequency transmission. An inverter is used to transform DC to AC of low frequency, preferably of 1/3 of the normal power frequency. The low frequency AC voltage is transformed to higher voltages for efficient transmission. The above-described basic approach produces a number of alternative topologies for specific geographical arrangements. In addition, it will allow the development of other forms of storage systems, such as hydro or pumped hydro that may be located in remote areas.

# CHAPTER 2

# BACKGROUND AND LITERATURE REVIEW

## 2.1 Introduction

In recent years the amount of electricity produced from wind has grown rapidly. Large wind farms located remotely or offshore are used to meet the increasing power demand. This requires transmission of power over long distances. In this study, low frequency AC (LFAC) transmission technology is proposed for various designs of the wind farms.

## 2.2 Technologies for Wind Farm Power Transmission

The possible solutions for transmitting power from wind farms are HVAC, Line commutated HVDC and voltage source based HVDC (VSC-HVDC). Low frequency AC transmission (LFAC) is particularly beneficial in terms of cost savings and reduction of line losses [4] in cases where the distance from the power generating stations to the main power grid is large. The use of fractional frequency transmission system (FFTS) for offshore wind power is discussed in [6]. The author proposes LFAC as an alternative to HVAC and HVDC technologies for a short and intermediate transmission distances. HVAC is more economical for short transmission distances. For longer distances, HVAC has disadvantages like increase in the cable cost, terminal cost and charging.

HVDC transmission systems and wind farm topologies are discussed in [12]. HVDC being a matured technology is used for longer distances. Compared to HVDC, the LFAC system reduces the usage of an electronic converter terminal which reduces the investment cost. HVDC technology is used only for point-to-point transmission [11], and LFAC can be used for similar networks as AC transmission.

Further, VSC-HVDC replaces the thyristors with IGBTs and is considered to be the most feasible solution for long distance transmission. However, addition of converter stations on both sides of the transmission line increase the investment cost of the VSC-HVDC system [7] compared to LFAC.

Hence, due to the limitations of the HVAC and HVDC the proposed LFAC is used in the design of transmission systems. The use of LFAC can be extended to long transmission distances. Cyclo converter technology is used for converting the AC of nominal frequency to AC of one third frequency i.e. 16.67 Hz/20 Hz for a 50 Hz/ 60 Hz transmission system`. Several advantages of the LFAC are identified. The transmission system used for conventional AC system can be used for LFAC without any modifications and the LFAC system increases the transmission capacity.

## 2.3 Wind Farm Connections and Cost Analysis

Thomas et al., [2] proposed that a series connection of the wind farm leads to the elimination of the offshore platform and the turbines' output would be DC. As a result the desired high transmission voltage can be obtained directly without a large centralized DC/DC converter. Various wind farm designs are proposed based on this idea with low frequency and nominal frequency transmissions.

Lundberg [7, 8] presents various wind farms and energy production costs for these wind farms. The different electrical configurations for the wind farm discussed are large AC, AC/DC, small DC, large DC and series DC system. A result of the study is that a series DC wind farm has promising energy production cost, if the transmission distance is above 20 km.

Wind power is an intermittent source of energy. The author in [1] presents a computationally efficient recursive algorithm to calculate the wind farm power output distribution. The model focuses on generation and transmission system reliability. In the present study various wind farm configurations are designed to determine the total cost of the energy production and transmission system reliability issues need to be addressed.

Increased penetrations of wind energy cause operational problems to the utility grid [3]. An AC/DC/AC interface resolves the operational problems caused due to the increased wind energy penetration by introducing protection and coordinated control of the wind farm output.

The goal of this thesis is to evaluate alternative transmission systems from remote wind farms to the main grid using LFAC. The wind farm design, cost and efficiency of the transmission system influence the economics of the overall system [12]. The main focus of this thesis is to develop comprehensive methodology for determining the optimal topology and optimal transmission voltage for a LFAC system.

# CHAPTER 3

# TOPOLOGIES FOR LOW FREQUENCY TRANSMISSION

## 3.1 Introduction

The literature survey indicates that many topologies and systems have been proposed for transmitting power from wind farms to the main power grid. In this section a number of topologies and systems are presented that are further evaluated for their costs and operating voltages.

### 3.2 Wind farm topologies

A wind farm is a group of interconnected wind turbines located in the same geographical area. Individual wind turbines are interconnected by medium voltage power collection system. In order to connect the local wind turbine grid to the transmission system the voltage is increased. A wind farm contains the following elements: wind turbines, local wind turbine grid, collecting point, transmission system and wind farm interface to the point of common connection (PCC). The power from the wind turbine units is collected at the collecting point where the voltage is increased to a level suitable for transmission. The power is then transmitted to the wind farm grid interface over the transmission system. The following are the different wind farm topologies:

#### 3.2.1 Wind system configuration 1: AC wind farm, Nominal frequency, Network connection

Wind farms that are built today have an AC electrical system from the wind turbines to the PCC. Two different types of AC wind farms referred in this thesis are radial and network connections. Radial wind farms are suitable for small wind farms with a short transmission distance. In a small AC wind farm, the local wind farm grid is used both for connecting all wind turbines in a radial fashion and transmitting the generated power to the wind farm grid interface. Network connected wind farms are usually large AC wind farms where the local wind farm grid has a lower voltage level than the transmission system.

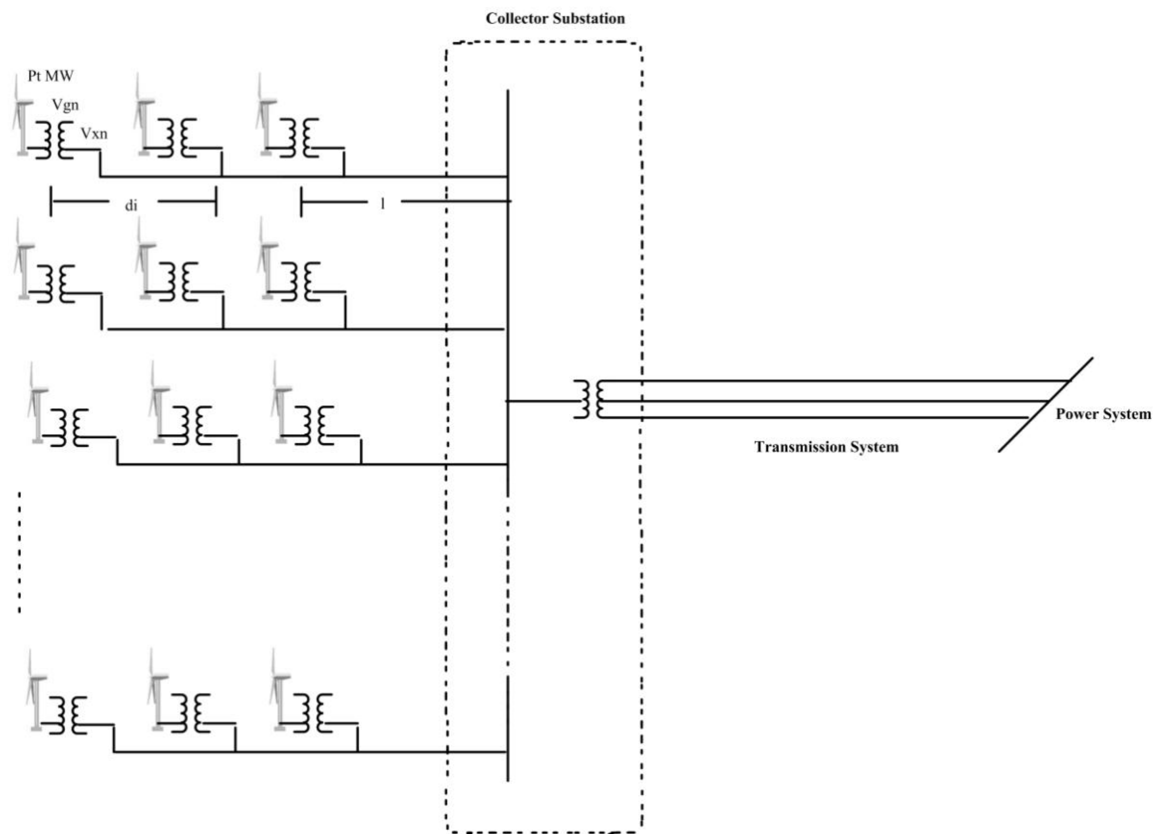


Figure 3.2.1: Wind system configuration 1: AC wind farm, Nominal frequency, Network connection

The wind system configuration 1 shown in figure 3.2.1 has network connection of wind turbines and AC power collection system. The configuration is described with the following parameters:

$n_f$ : Number of radial feeders

$m_i$ : Number of wind turbines in radial feeder i

$d_i$ : Distance between adjacent wind turbines in feeder i (feet)

l: Distance between the last wind turbine and the collector substation (feet)

$P_t$ : Power rating of the wind turbine (MW)

$V_{gn}$ : Nominal generator voltage (kV)

$V_{xn}$ : Nominal high side transformer voltage (kV)

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

For the parametric study the following parameters are considered: Wind turbine system (WTS) rating (Pt): 1MW, 1.75MW, 2.25MW or 3.6MW. Distance between two adjacent wind turbine systems $d_i$ is fixed based on the rating of the wind turbine (WTS of 1 MW, $d_i$= 300 ft, WTS of 1.75 MW, $d_i$= 500 ft, WTS of 2.25 MW, $d_i$ = 600 ft, WTS of 3.6 MW, $d_i$ = 700 ft). Medium voltage cable size: 1/0, 2/0, 3/0, 4/0, 250 KCM, 350 KCM, 500 KCM and 750 KCM and rated voltage: 5 kV, 15 kV and 28 kV. Cost of cable is obtained from South wire.

### 3.2.2 Wind System Configuration 2: AC Wind Farm, AC/DC Transmission, Network Connection

The wind system configuration 2 shown in figure 3.2.2 is similar to the wind system configuration 1 except for the transmission part from the collector substation to the main power grid. AC transmission is replaced by DC transmission in this configuration. Nominal frequency transmission is adopted within the wind farm. This wind farm is referred to as AC/DC wind farm. This type of system does not exist today, but is frequently proposed when the distance to main grid is long. The wind system configuration 2 is also described with the same parameters as the wind system configuration 1.

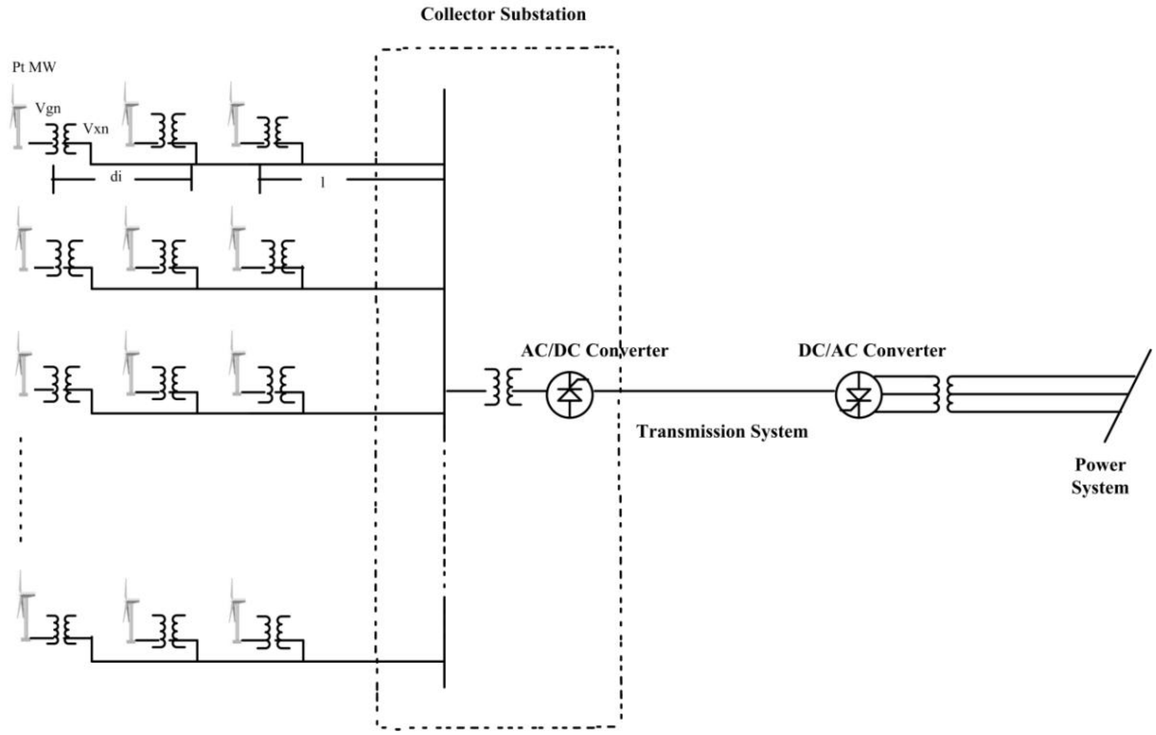

Figure 3.2.2: Wind system configuration 2: AC wind farm, AC/DC transmission, Network connection

### 3.2.3 Wind system configuration 3: Series DC Wind farm, Nominal frequency, Network connection

The wind system configuration 3 has a DC power collection system. Wind turbines are connected in series and each set of series connected array is connected to the collection point. Using DC/AC converters, AC of suitable voltage level and nominal frequency is generated. Voltage is stepped up and the power is transmitted to the interconnection point at the power grid by a high voltage transmission line.

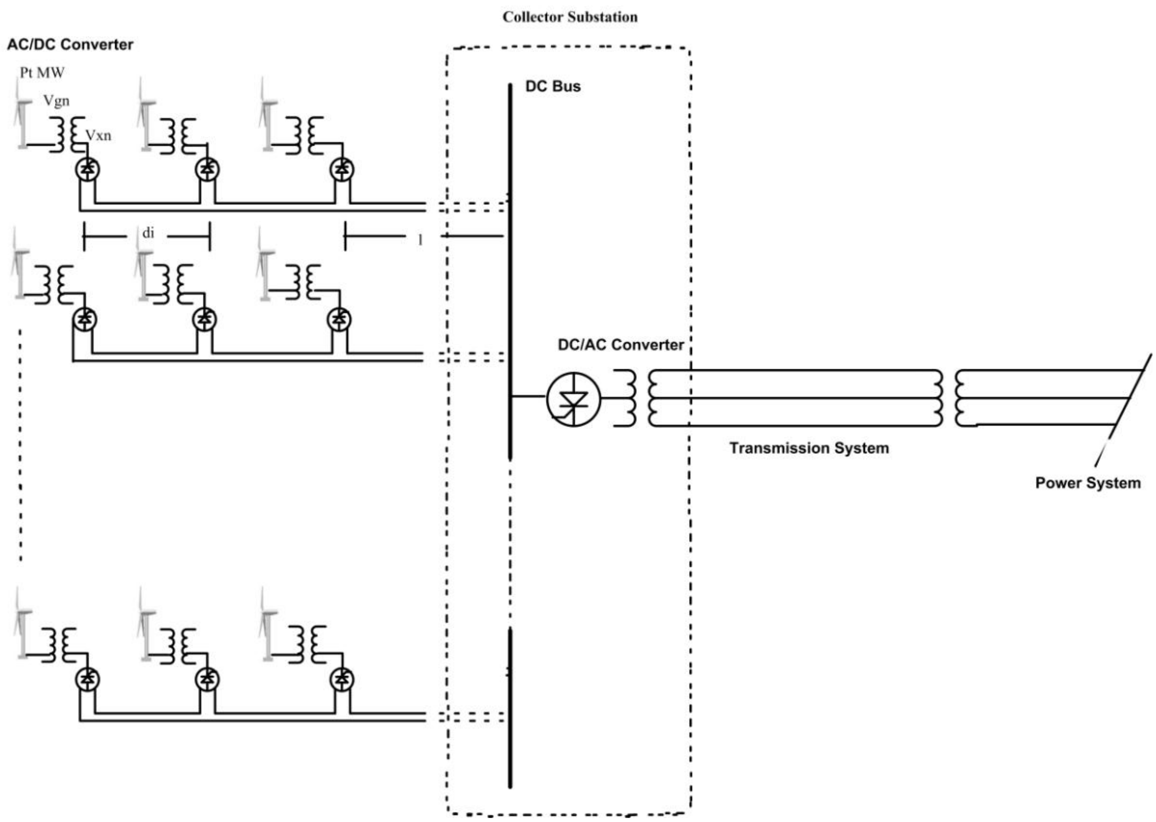

Figure 3.2.3: Wind system configuration 3: Series DC Wind farm, Nominal frequency, Network connection

The wind system configuration 3 as shown in figure 3.2.3 is described with the following parameters:

$n_f$ : Number of radial feeders

$m_i$ : Number of wind turbines in radial feeder i

$d_i$ : Distance between adjacent wind turbines in feeder i (feet)

l: Distance between the last wind turbine and the collector substation (feet)

$P_t$ : Power rating of the wind turbine (MW)

$V_{gn}$ : Nominal generator voltage (kV)

$V_{xn}$ : Nominal high side transformer voltage (kV)

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

### 3.2.4 Wind System Configuration 4: Parallel DC Wind Farm, Nominal Frequency, Network Connection

Wind system configuration 4 differs from the wind system configuration 3 in the local wind farm design. Here a number of wind turbine systems are connected in parallel and each set of parallel connected wind turbines are connected to a collection point. Using DC/AC converters, AC of suitable voltage level and nominal frequency is generated. At the collection point voltage is stepped up by means of a transformer and the power is transmitted to the interconnection point at the power grid by a high voltage transmission line.

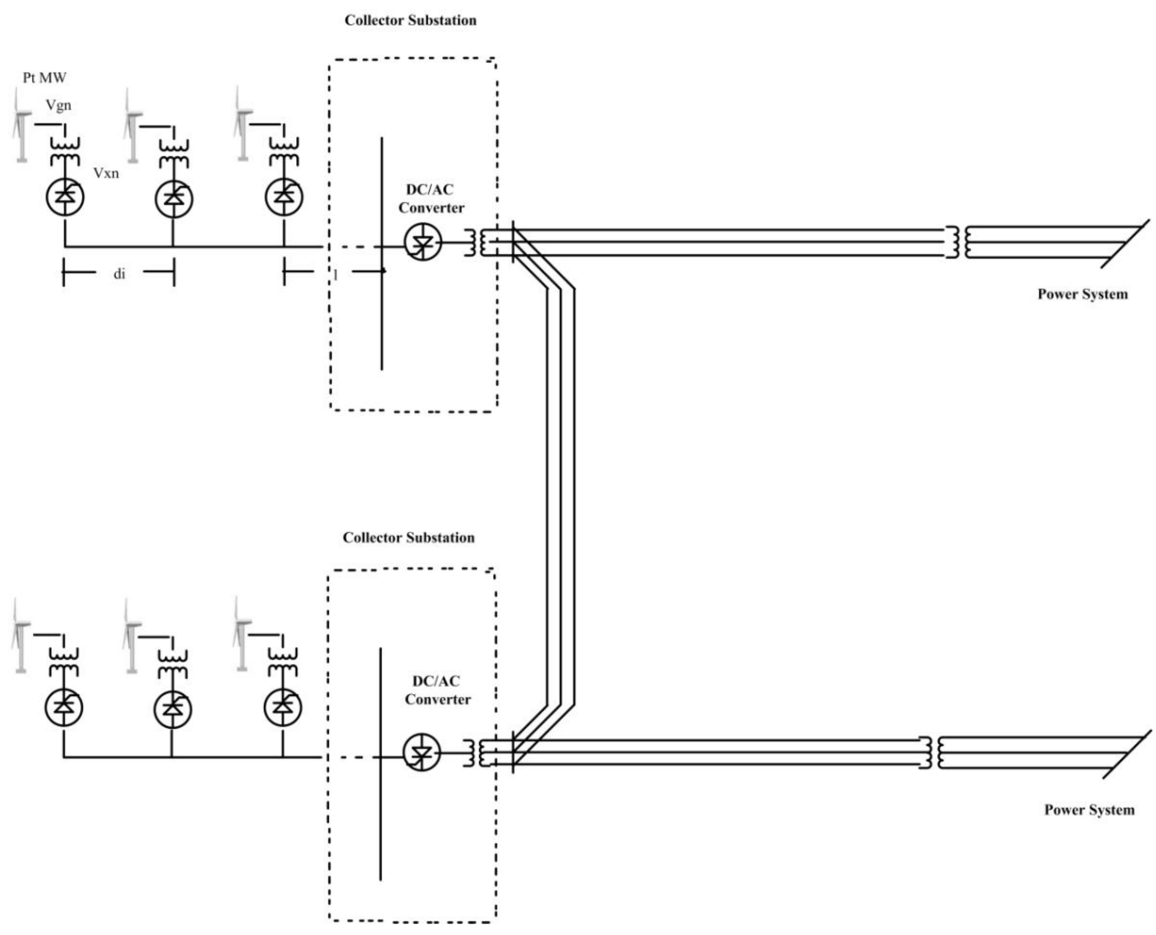


Fig. 3.2.4: Wind system configuration 4: Parallel DC Wind farm, Nominal frequency, Network connection

Two small sized wind farms are interconnected via a transmission line to ensure reliable supply of power to the main grid in the event of fault or maintenance shut down in any one of the wind farms by transferring power generated from the other wind farm.

The wind system configuration 4 as shown in Figure 3.2.4 is described with the following parameters:

$n_f$ : Number of radial feeders

$m_i$ : Number of wind turbines in radial feeder i

$d_i$ : Distance between adjacent wind turbines in feeder i (feet)

l: Distance between the last wind turbine and the collector substation (feet)

$P_t$ : Power rating of the wind turbine (MW)

$V_{gn}$ : Nominal generator voltage (kV)

$V_{xn}$ : Nominal high side transformer voltage (kV)

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

### 3.2.5 Wind System Configuration 5: Series DC Wind Farm, Low Frequency Radial AC Transmission

The wind system configuration shown in figure 3.2.5 has a DC wind farm. Here a number of wind turbine systems are connected in series and each series string is connected to a collection point. An inverter is used to convert DC to AC of low-frequency preferably one third the nominal power frequency at the collection point. The voltage is raised to higher kV levels by means of a transformer (standard transformers are used with appropriately reduced ratings for the low frequency). The power is transmitted to the main power grid via lines operating at low frequency. Using cyclo-converters the low frequency is converted to power frequency before connecting to the main power grid.

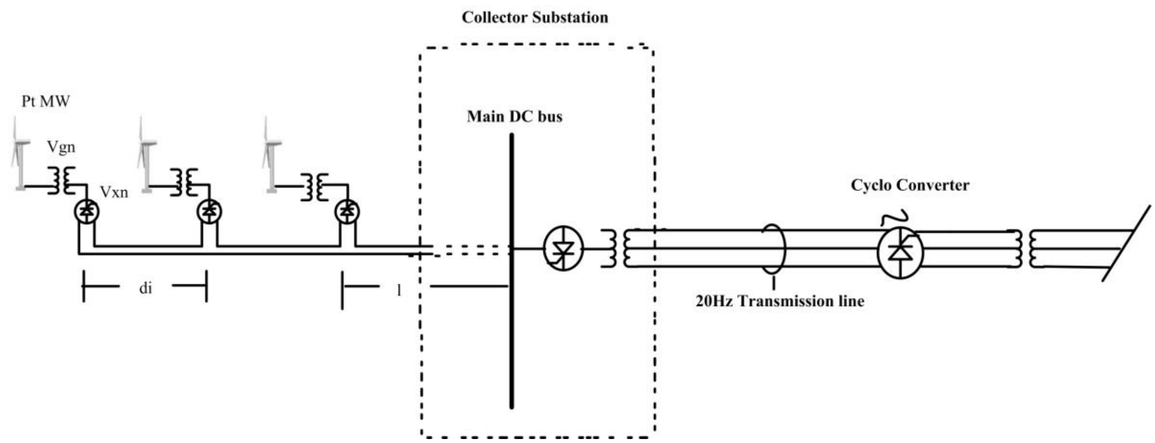


Figure 3.2.5: Wind system configuration 5: Series DC wind farm, Low frequency radial AC transmission

The wind system configuration 5 has the same parameters as wind system configuration 3.

### 3.2.6 Wind System Configuration 6: Parallel DC Wind Farm, Low Frequency, Radial Transmission

Wind system configuration 6 is similar to the wind system configuration 5. Here the difference is that the wind turbines are connected parallel to each other and to the collection point. Parallel connection of wind turbines leads to same voltage across the terminals of all the wind turbine systems. The generated power is converted to low-frequency AC using inverter and transmitted over long distances to the power grid. Cyclo-converter technology is used to convert the low frequency to nominal frequency before connecting the system to the main power grid.

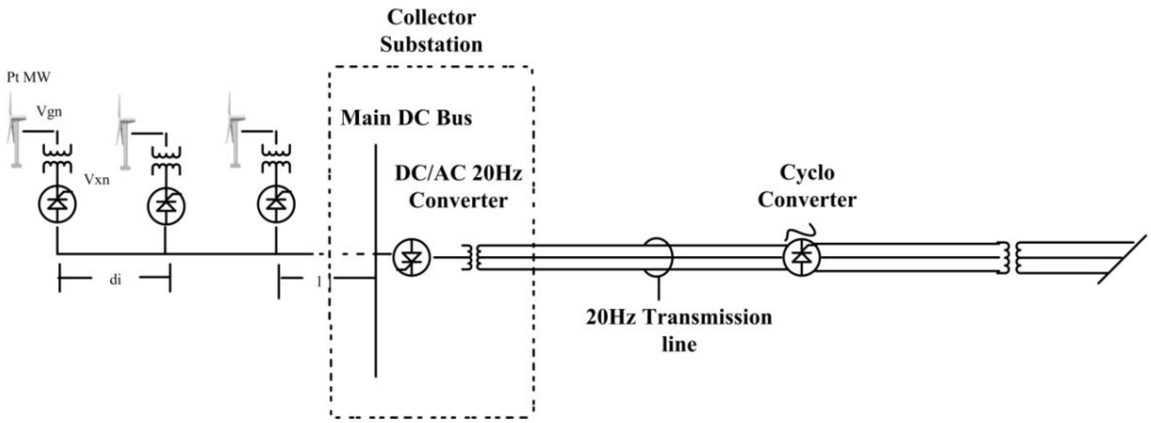


Figure 3.2.6: Wind system configuration 6: Parallel DC Wind Farm, Low frequency, Radial transmission

The wind system configuration 6 has the same parameters as wind system configuration 4.

### 3.2.7 Wind System Configuration 7: Series DC Wind Farm, Low Frequency AC Transmission Network

Here a number of wind turbine systems are connected in series and each set of series connected array is connected to a collection point. At the collection point DC is converted to low frequency AC by means of inverters. The transmission of power up to the main power grid is by means of a network of transmission lines operated at low frequency. The low frequency AC system is connected to the power grid by means of cyclo-converters.

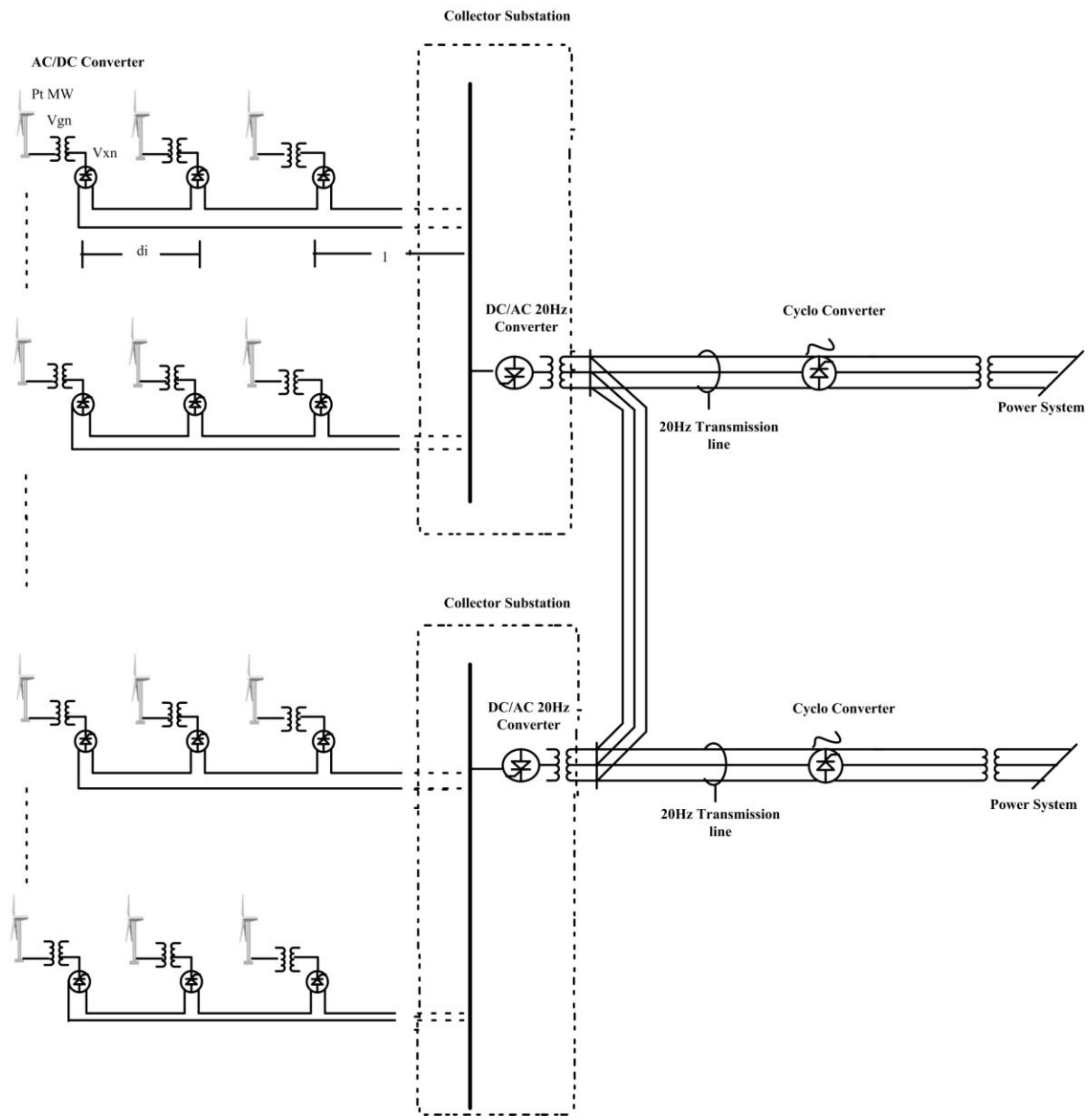


Figure 3.2.7: Wind system configuration 7: Series DC wind Farm, Low frequency AC transmission Network

The wind system configuration 7 as shown in Fig. 7 has the same parameters as wind system configuration 3.

### 3.2.8 Wind System Configuration 8: Parallel DC Wind Farm, Low Frequency AC Transmission Network

Wind system configuration 8 has a number of wind turbine systems connected in parallel and each set of parallel connection of wind turbine systems are connected to a collection point. From the collection point to power grid system is identical to wind system configuration 7.

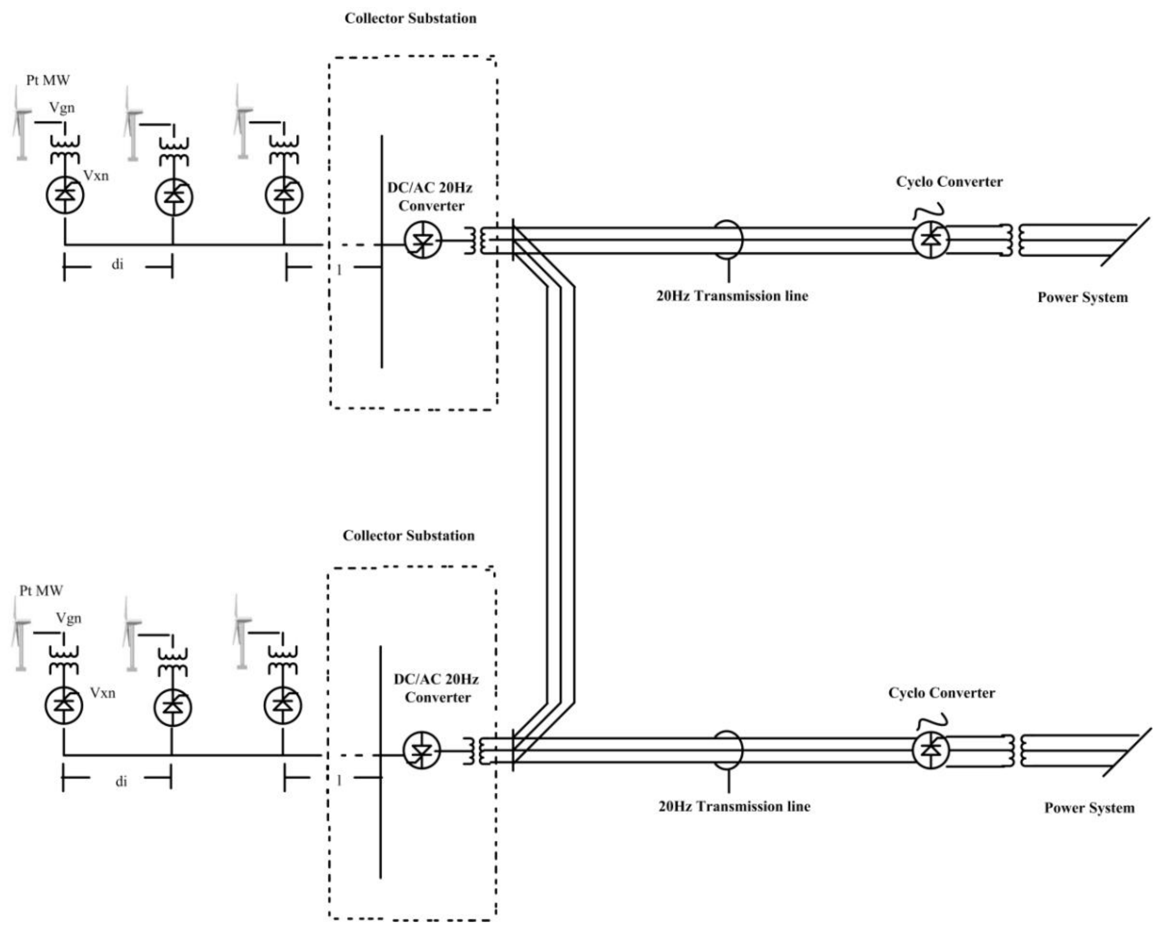


Figure 3.2.8: Wind system configuration 8: Parallel DC wind Farm, Low frequency AC transmission Network

The wind system configuration 8 as shown in Figure 3.2.8 has the same parameters as wind system configuration 4.

To summarize, the topologies of different wind system configurations have been discussed. The parameters which describe these wind system configurations are listed. Calculations in chapter 4 are based on these parameters. For a particular geographical location depending on the wind statistics and land availability the wind farms are designed.

# CHAPTER 4

# VOLTAGE LEVEL SELECTION

This section provides analysis and results that determine the optimal transmission voltage used in the alternative wind transmission systems up to the main DC bus. The optimal kV level for transmission within the wind farm is selected by evaluation of the total costs consisting of operational costs (mainly losses) and annualized investment cost. The cost of the auxiliary equipment is not considered. The power loss during transmission in a wind farm is a function of the following parameters:

- Size of the medium voltage cable
- Distance between two adjacent wind turbines
- Number of wind turbines
- Number of radial feeders
- Voltage rating of the wind turbine system transformer
- Voltage rating of the transformer at the collection point
- Interest rate charged on the acquired components
- Life time of the equipment and the cable

The optimal kV level is selected on the basis of minimal total cost consisting of operating costs (mainly transmission loss) and investment cost. Calculations to determine the losses in $ per year and the annual investment cost are discussed in this chapter.

## 4.1 Voltage calculation 1 - Wind system configuration 5: Series DC wind farm, Low frequency radial AC transmission:

Wind system configuration 5 has a series DC wind farm as shown in figure 4.1 where $m_i$ wind turbines are connected in series to obtain the suitable transmission voltage. The wind turbine systems are assumed to be identical, thus resulting in same voltage and current through them. A wind farm rated 30 MW consisting of 10 wind turbines each rated 3 MW is considered. The transmission voltage for calculation purpose is selected as 35 kV. Thus, the nominal high side transformer voltage for the wind turbines is 3.5 kV. The optimal transmission voltage is obtained by plotting the values obtained from the calculation of loss and the annual investment cost of the cable and converter for different values of the transmission voltage.  The resistance of the chosen cable is approximately 0.0153 ohm/ 1000 ft.

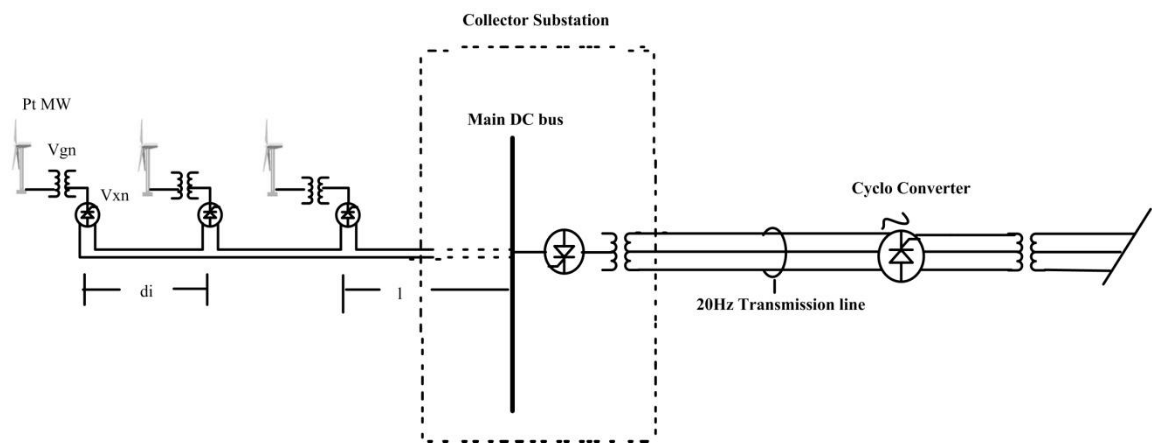


Figure 4.1: Wind farm configuration 1: Series DC wind farm, radial connection

### 4.1.1 Calculation of transmission loss (up to the main DC bus) ($/yr)

The following equations are used to determine the transmission loss with in the wind farm.

$$P_t = I_{dc} V_{xn} \quad (1)$$

$$V_{xn} = \frac{V_{dc}}{m_i} \quad (2)$$

$$I_{dc} = \frac{P_t}{V_{xn}} \quad (3)$$

$$R = 2r(l + (m_i - 1)d) \quad (4)$$

$$P_L = I_{dc}^2 R \qquad (5)$$

Where,

$n_f$ : Number of radial feeders = 1

$m_i$ : Number of wind turbines in radial feeder i = 10

$d_i$ : Distance between adjacent wind turbines in feeder i (feet) = 500 ft

l : Distance from the last wind turbine to the collection point = 600ft

$P_t$ : Power rating of the wind turbine (MW) = 3 MW

$V_{gn}$ : Nominal generator voltage = 0.575 kV

$V_{dc}$: Nominal DC bus voltage = 35 kV

$V_{xn}$ : Nominal high side transformer voltage = 3.5 kV

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

$I_{dc}$ : DC current in the DC circuit [Amperes]

$r$ : Resistance of cable per unit length = 0.0153 ohms/1000ft

$P_L$ : Transmission power loss [MW]

Substituting the above values in (1), (2), (3), (4) and (5) we get:

$I_{dc}$ = 857 A

$R$ = 0.156 ohms

$P_L$ = 0.1145 MW

C: Cost of electricity = $100/ MWh

$$Loss\,in\,\$/yr = (8760)\, n_f\, C\, P_L \qquad (6)$$

This formula assumes that the wind farm operates continuously at maximum power which is unrealistic. The capacity factor of a wind turbine is approximately 30% [1]. Hence the resultant Loss in $/yr is multiplied by 0.3.

Therefore, Loss = $ 30,110 /yr.

### 4.1.2 Calculation of Cost of cable and the converter equipment in $/yr

The acquisition cost of the cable is $ 18.5 /ft. To calculate the cost of cable required for the entire wind farm, the length of the cable is calculated. Multiplying the acquisition cost of cable by the total length of the cable gives the acquisition cost of the cable for the entire wind farm in $.

$$L = 2n_f\,(l + (m_i - 1)d) \tag{7}$$

$$CCost = n_f\,L\,ACost \tag{8}$$

L: Total length of the cable up to the collection point [feet]

CCost: Acquisition cost of cable for entire wind farm [$]

ACost: Acquisition cost of the cable per feet = $ 18.5 /ft

Total length of cable, $L$ = 10,200 ft

Therefore, acquisition cost of the cable, CCost = $ 188,700/yr.

The cost of converter is given by

$$Cost_{conv} = (0.5)\,m_i n_f\,Cost_{inv}\left(1 + \left(\frac{V_{xn}}{690}\right)^{0.5}\right) \tag{9}$$

$Cost_{conv}$: Cost of converter [$]

$Cost_{inv}$: Cost of inverter = 14,692 $

The above calculation gives the acquisition cost of converters to be $238,907. Assuming an interest rate of 6% and the life time of the cable and the converter to be 20 years, the annual amortization is calculated. Acquisition cost of the cable and the converters is $ 427,607.

$$A = P\,\frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

P: Acquisition cost of cable and converter = 427,607 $

A: Annual investment for cable and converter [$/yr] i: Interest rate= 6%

N: Life time = 20 years

Thus, the annual investment for cable and converter is $ 37,244 /yr. For determining the optimal operating voltage, $V_{dc}$ vs. Loss ($/yr) and $V_{dc}$ vs. Annual investment for cable and converter ($/yr) are plotted. The optimal voltage level is determined by the lowest point of the curve obtained by adding the Loss ($/yr) and Annual investment cost ($/yr) as shown in figure 4.2.

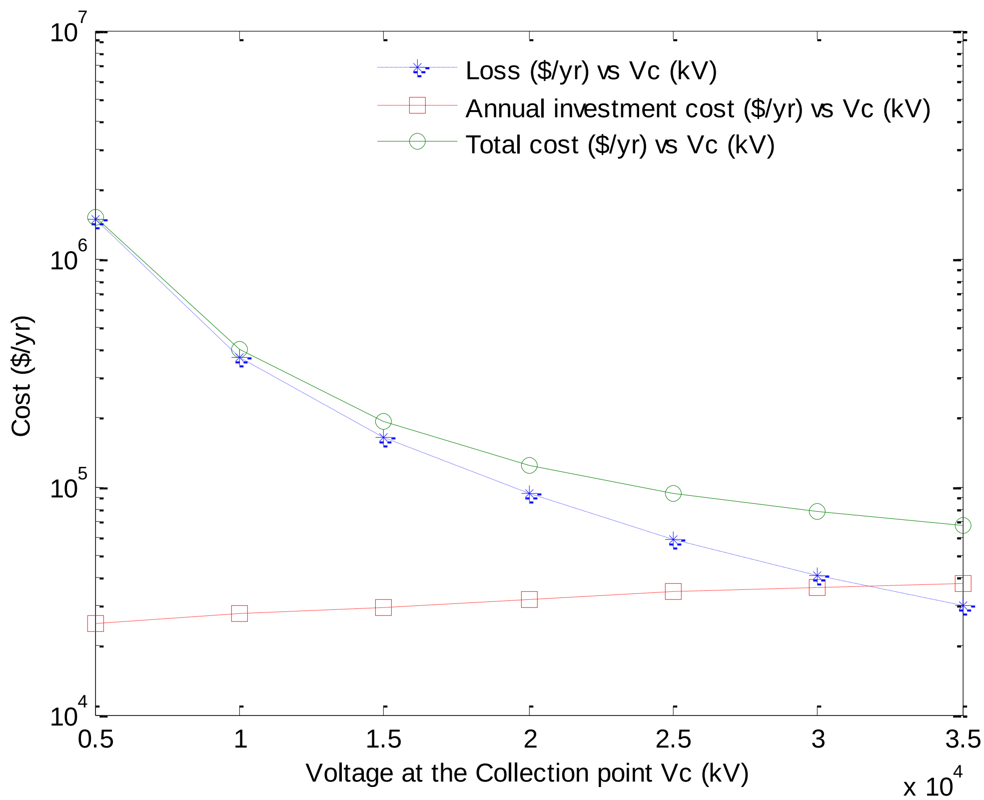


Figure 4.2: Plot of voltage at Che main DC bus vs. total cost for $m_i$=10, Pt = 3MW

From the plot in figure 4.2 it can be seen that for the wind farm rated 30 MW having 10 wind turbines the optimal voltage would be around 35kV. As the voltage level further increases the transmission power loss decreases but the cost of the cable and the converter increases. The plots of annual investment cost vs. $V_{dc}$ and loss vs. $V_{dc}$ intersect at 32 kV, from that point the annual investment cost goes on increasing. The optimal voltage is obtained by determining the lowest point on the graph obtained by adding the annual investment cost and the loss in $/yr. The x coordinate of the point is the optimal transmission voltage which is 35 kV in this case. For different wind turbine ratings, cable size and the wind farm size the optimal level of voltage is calculated in a similar fashion as shown above.

### 4.2 Voltage level selection 2 - Wind system configuration 3: Series DC wind farm, Nominal frequency, Network connection:

Here we consider wind system configuration 3 and 7. Both topologies have same wind farm configurations. They have $m_i$ wind turbines connected in series on each radial feeder and $n_f$ radial feeders forming a network connection. All the wind turbine systems are assumed to be identical, thus resulting in same voltage and current through them. In this case, wind turbines rated 2 MW and 5 radial feeders are considered with 5 wind turbines on each feeder. The rated power of the wind farm is assumed to be 100 MW. The transmission voltage is selected as 35 kV, which makes the nominal high side transformer voltage for the wind turbines to be 7 kV.

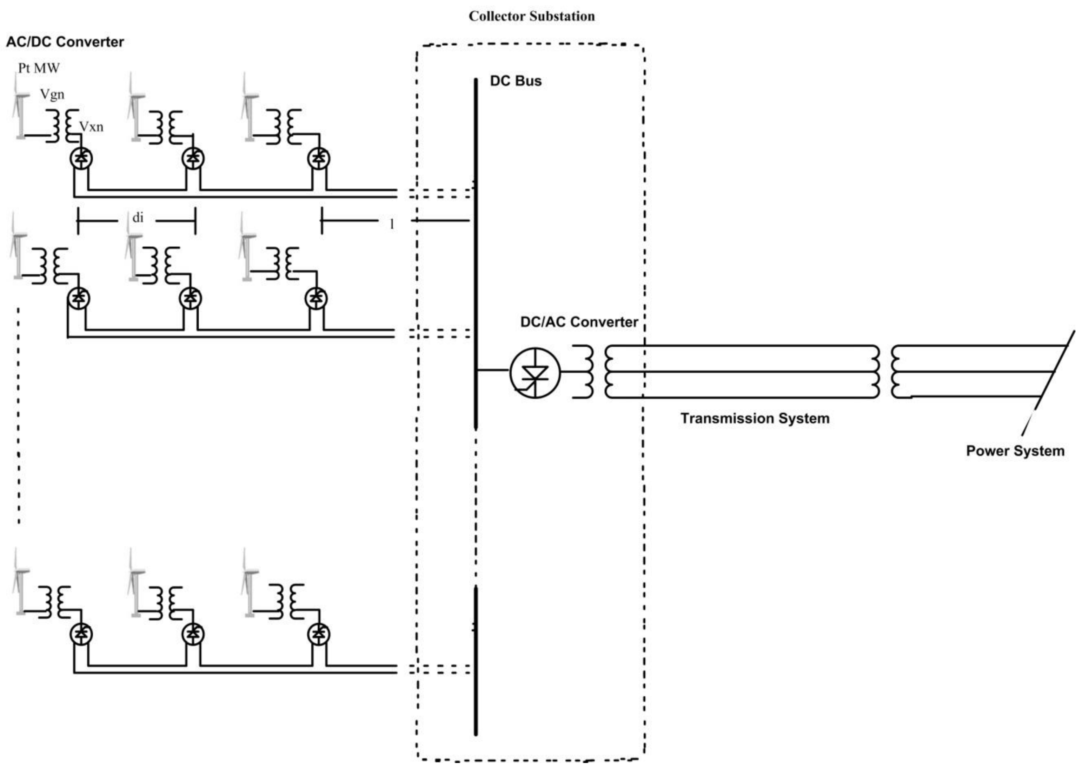


Fig. 4.3: Wind system configuration 3: Series DC wind farm, nominal frequency, network connection

### 4.2.1 Calculation of transmission loss (up to the Main Dc Bus) ($/yr)

The equations (1), (2), (3), (4) and (5) are used to determine the transmission loss within the wind farm.

Where,

$n_f$ : Number of radial feeders = 5

$m_i$ : Number of wind turbines in radial feeder i = 5

$d_i$ : Distance between adjacent wind turbines in feeder i (feet) = 500 ft

l : Distance from the last wind turbine to the collection point = 600ft

$P_t$ : Power rating of the wind turbine (MW) = 2 MW

$V_{gn}$ : Nominal generator voltage = 0.575 kV

$V_{dc}$: Nominal DC bus voltage = 35 kV

$V_{xn}$ : Nominal high side transformer voltage = 7 kV

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

$I_{dc}$ : DC current in the DC circuit [Amperes]

$r$ : Resistance of cable per unit length = 0.0153 ohms/1000ft

$P_L$ : Transmission power loss [MW]

Substituting the above values in (1), (2), (3) and (4) we get:

$I_{dc}$ = 285.7 A

$R$ = 0.0796 ohms

$P_L$ = 0.0324 MW

$P_L$ here is the transmission power loss for the whole wind farm which includes 25 wind turbines. Loss in $/yr is multiplied by 0.3 to account for the capacity factor.

Therefore, Loss = $ 8,514 /yr.

### 4.2.2 Calculation of Cost of cable and the converter equipment in $/yr

The acquisition cost of the cable is $ 18.5 /ft. To calculate the cost of cable required for the entire wind farm, the length of the cable is calculated. Multiplying the acquisition cost of cable by the total length of the cable gives the acquisition cost of the cable for the entire wind farm in $. Equations (8) and (9) are used to calculate the length of the transmission cable and acquisition cost of the cable respectively.

L: Total length of the cable up to the collection point [feet]

CCost: Acquisition cost of cable for entire wind farm [$]

ACost: Acquisition cost of the cable per feet = $ 18.5 /ft

Total length of cable, $L$ = 26,000 ft

Therefore, acquisition cost of the cable, CCost = $ 481,000 /yr.

Using equation (9) the acquisition cost of converter is calculated to be $768,595.

Assuming an interest rate of 6% and the life time of the cable and the converter to be 20 years, the annual amortization is calculated using equation (10). Thus, acquisition cost of the cable and the converter is $ 1,249,595.

P: Acquisition cost of cable and converter = 1,249,595 $

A*:* Annual investment for cable and converter [$/yr]

i: Interest rate= 6%

N: Life time = 20 years

Thus, the annual investment for cable and converter is $ 108,714 /yr. For determining the optimal voltage ($V_{dc}$), $V_{dc}$ vs. loss ($/yr) and $V_{dc}$ vs. annual investment for cable and converter ($/yr) are plotted. The optimal voltage level is determined by the lowest point of the curve obtained by adding the loss ($/yr) and annual investment ($/yr) curves.

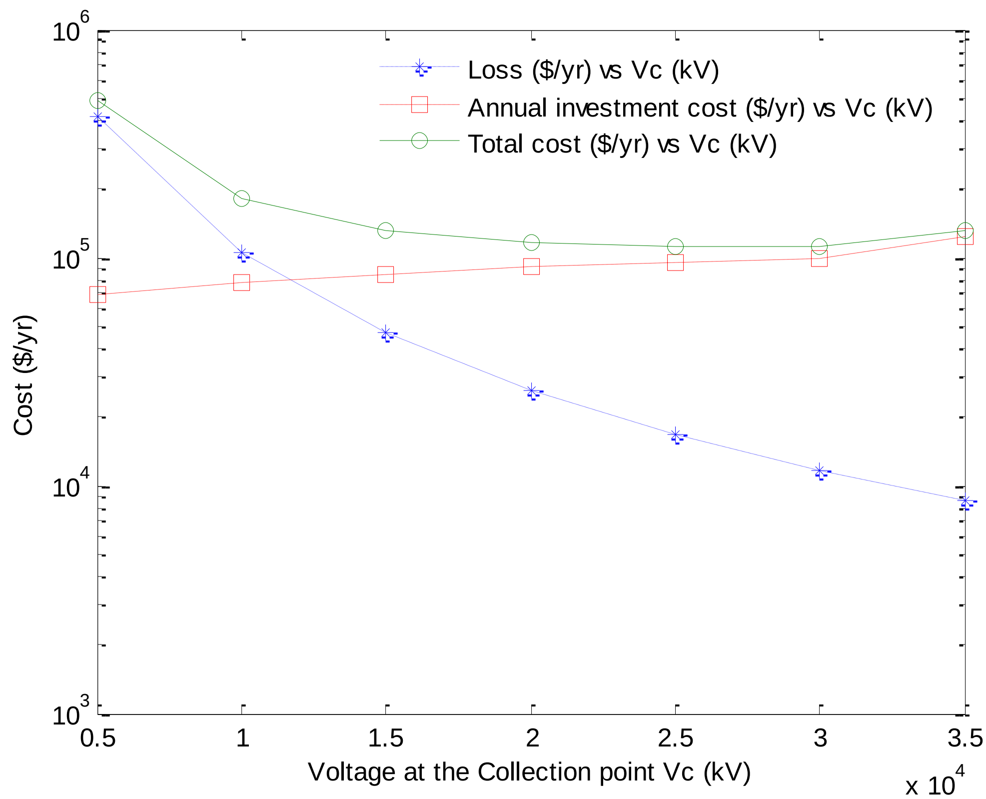


Figure 4.4: Plot of voltage at the main DC bus vs total cost for $m_i$= 5, $n_f$ =5, Pt = 2 MW

From the plot in figure 4.4 it can be seen that, for this case with a wind farm rated 100 MW having 25 wind turbines rated 2 MW each, the optimal voltage would be 30 kV. This is the lowest point on the curve obtained by adding the loss ($/yr) and annual investment cost of cable and converters ($/yr). As the voltage level further increases the power loss decreases but the cost of the cable and the converter increases. Higher the transmission voltage, lower would be the losses but the cost of transmission cable and the converter increases. Thus, to make the system economical, optimal voltage level is chosen as the lowest point on the total cost curve which is 30 kV.

## 4.3 Voltage level selection 3 - Wind system configuration 6: Parallel DC wind farm, low frequency, radial connection

The wind farm design of wind system configuration 6 has $m_i$ wind turbines connected in parallel to each other and to the collection point. The power generated is collected and transmitted to the gird using low frequency AC transmission. All the wind turbine systems are assumed to be identical, thus resulting in same voltage and current through them. Here 10 wind turbines each rated 3 MW are chosen. The rated power of the wind farm is assumed to be 30 MW. The transmission voltage is chosen to be 25 kV for calculation purpose. Thus, the nominal high side transformer voltage connected to the wind turbines is 25 kV. The optimal transmission voltage for this case is calculated based on the annual investment cost and the transmission power loss for different voltage ranges from 5 kV to 35 kV.

### 4.3.1 Calculation of transmission loss (up to the Main Dc Bus) ($/yr)

The following equations are used to calculate the transmission loss in the wind farm up to the collection point.

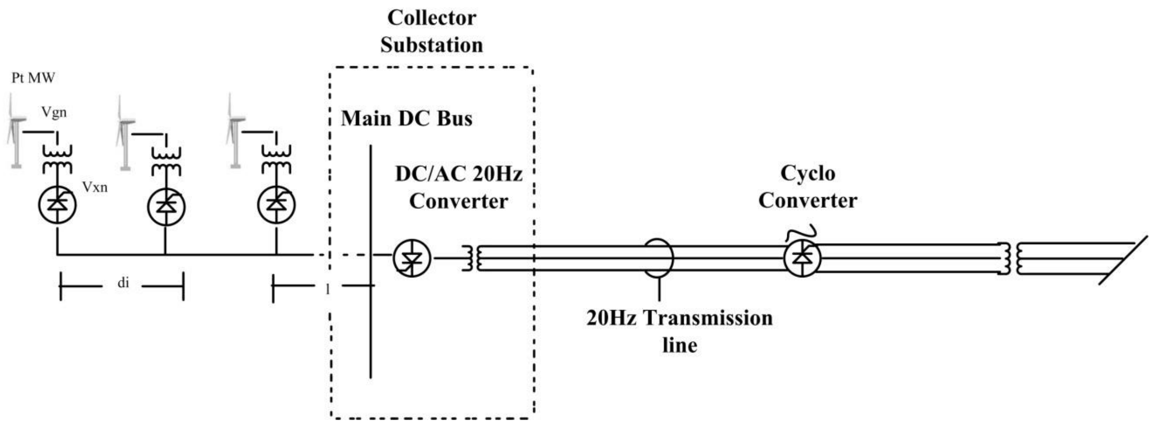


Figure 4.5: Wind system configuration 6: Parallel DC wind farm, low frequency, radial connection

$$P_L = 2I_1^2 r d_i + 2I_2^2 r d_i + \ldots 2I_{mi}^2 r l \qquad (11)$$

$$I_m = I_1 + I_2 + \ldots I_{(m-1)i} \qquad (12)$$

Where,

$I_n$ : Current at $n^{th}$ wind turbine [Amperes]

n : Number of radial feeders = 1

$m_i$ : Number of wind turbines in radial feeder i = 10

$d_i$ : Distance between adjacent wind turbines in feeder i (feet) = 500 ft

l : Distance from the last wind turbine to the collection point = 600ft

$P_t$ : Power rating of the wind turbine (MW) = 3 MW

$V_{gn}$ : Nominal generator voltage = 0.575 kV

$V_{dc}$: Nominal DC bus voltage = 25 kV

$V_{xn}$ : Nominal high side transformer voltage = 25 kV

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

$I_{dc}$ : DC current in the DC circuit [Amperes]

*r* : Resistance of cable per unit length = 0.0215 ohms/1000ft

$P_L$ : Transmission power loss [MW]

$I_{dc}$ = 120 A

Cost of electricity = $ 100/ MWh

Loss in $/yr is calculated using (6).

Loss = $32,950 /yr.

### 4.3.2 Calculation of Cost of cable and the converter equipment in $/yr

The acquisition cost of the 25 kV cable is 12 $/ft. To calculate the cost of cable required for the entire wind farm, the length of the cable is calculated. Multiplying the acquisition cost of cable by the total length of the cable gives the acquisition cost of the cable for the entire wind farm in $. Equations (8) and (9) are used to calculate the acquisition cost of the cable for entire wind farm.

L: Total length of the cable up to the collection point [feet]

CCost: Acquisition cost of cable for entire wind farm [$]

ACost: Acquisition cost of the cable per feet = $ 12 /ft

Total length of cable, $L$ = 10,200 ft

Therefore, acquisition cost of the cable, CCost = $ 122,400 /yr.

The cost of converter is given by

$$Cost_{conv} = (0.5)\, m_i n_f \; Cost_{inv} \left( 1 + \left( \frac{V_{dc}}{690} \right)^{0.5} \right) \qquad (13)$$

$Cost_{conv}$: Cost of converter [$]

$Cost_{inv}$: Cost of inverter = 14,692 $

The above calculation gives the total acquisition cost of converters to be $515,637. Assuming an interest rate of 6% and the life time of the cable and the converter to be 20 years, the annual amortization is calculated. Acquisition cost of the cable and the converters is $ 638,037.

P: Acquisition cost of cable and converter = 638,037 $

A: Annual investment for cable and converter is calculated using equation (11)

i: Interest rate= 6%

N: Life time = 20 years

Thus, the annual investment for cable and converter is $ 55,509 /yr. For determining the optimal voltage ($V_{dc}$), $V_{dc}$ vs. Loss ($/yr) and $V_{dc}$ vs. Annual investment for cable and converter ($/yr) are plotted. The optimal voltage level is determined by the lowest point of the curve obtained by adding the loss ($/yr) and annual investment ($/yr) curves which is 35 kV for this wind system configuration with 10 wind turbines connected in parallel as shown in figure 4.6.

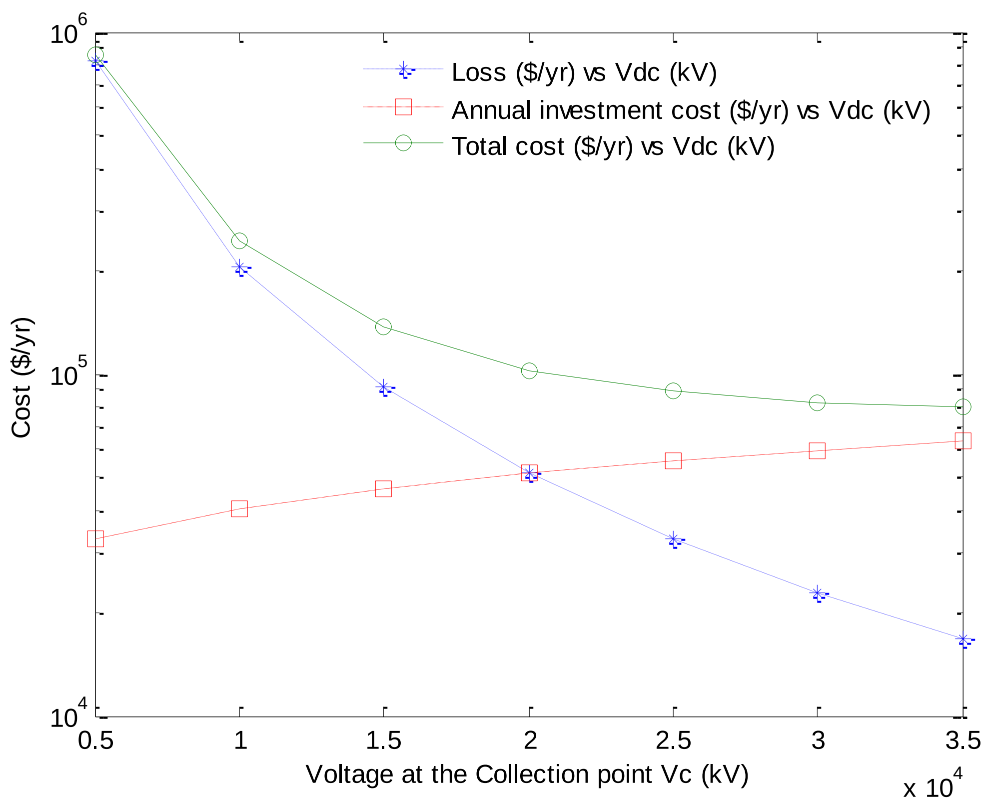


Figure 4.6: Plot of voltage at the main DC bus vs total cost for $m_i$= 10, $n_f$ =1, Pt = 3 MW

From figure 4.6 it can be seen that the cost of the transmission cable increases with increase in the voltage level and the losses in the transmission line decrease with increase in the voltage level. The lowest point on the total cost curve gives the optimal voltage. It is 35 kV for the wind farm configuration 6.

## 4.4. Voltage level selection – 4 Wind system configuration 4: Parallel DC wind farm, nominal frequency network connection

Wind system configurations 4 and 8 come under this case. Here the wind farm is constructed in such a way that $m_i$ wind turbines are connected in parallel and the power is collected at the collector substation. Likewise another $m_i$ wind turbines are connected in parallel and power is collected at the collector substation. These two sets of small wind farms are interconnected as shown in figure 4.7. Power from the substation is transmitted over long distances either by AC of nominal frequency as in Wind system configuration 4 or by AC of low frequency as in wind system configuration 8. In this case let there be 10 wind turbines in each set of the smaller wind farms. Rating of the wind turbines is assumed to be 3 MW with the rated capacity of wind farm to be 60 MW. Rated transmission voltage is assumed to be 25 kV.

### 4.4.1. Calculation of transmission loss (up to the Main Dc Bus) ($/yr)

The calculations for the transmission loss up to the collector bus station are similar to the wind farm configuration 6 as all the wind turbines are connected in parallel. There are two sets of smaller wind farms which are interconnected to supply power to the main grid. Thus the total transmission loss for this configuration is $ 65,900/yr.

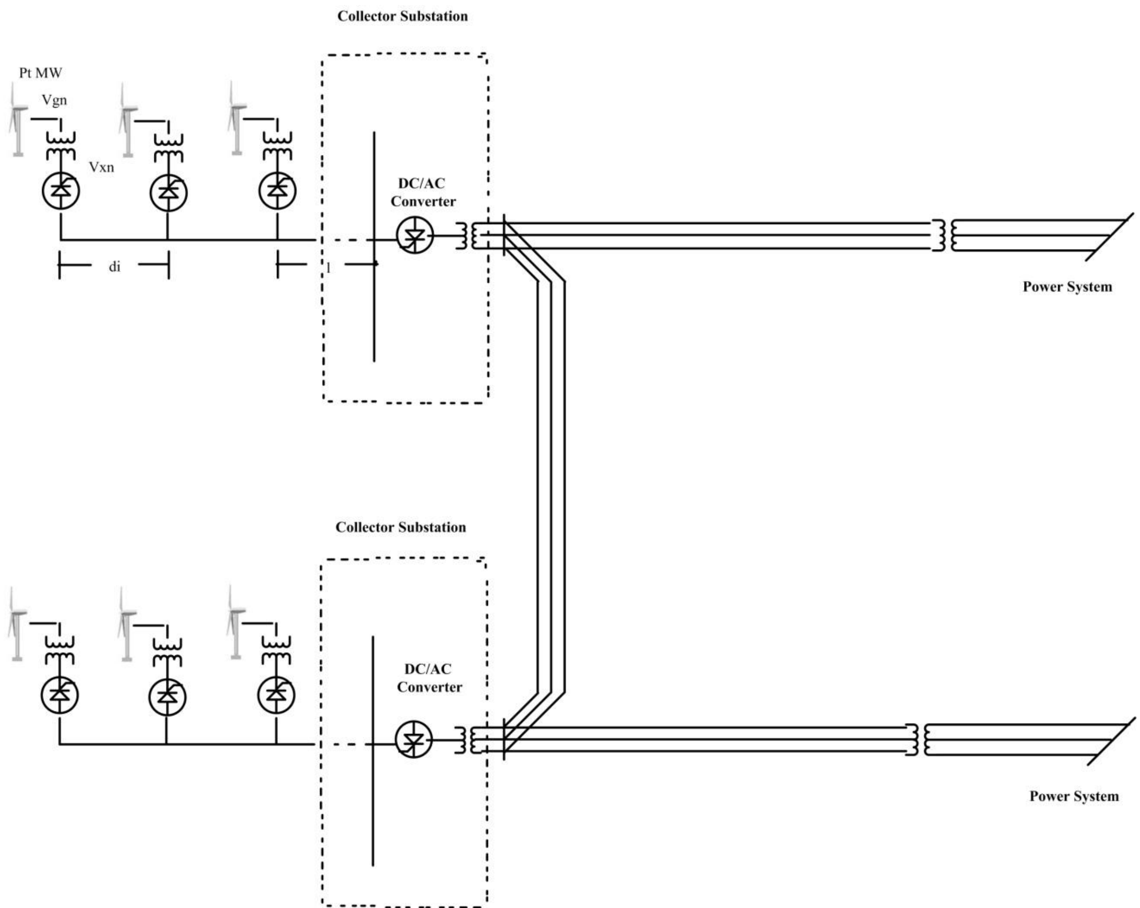

Fig. 4.7. Wind farm configuration 4: DC parallel wind farm, network connection

### 4.4.2. Calculation of Cost of cable and the converter equipment in $/yr

The cost of the cable and the converter equipment for this case is double the cost of the cable and converter equipment required for the wind farm configuration 6. Thus, the annual investment for cable and converter is $ 1,278,700 /yr. For determining the optimal voltage ($V_{dc}$), $V_{dc}$ vs. Loss ($/yr) and $V_{dc}$ vs. Annual investment for cable and converter ($/yr) are plotted. The optimal voltage level is determined by the lowest point of the curve obtained by adding the Loss ($/yr) and Annual investment ($/yr) curves.

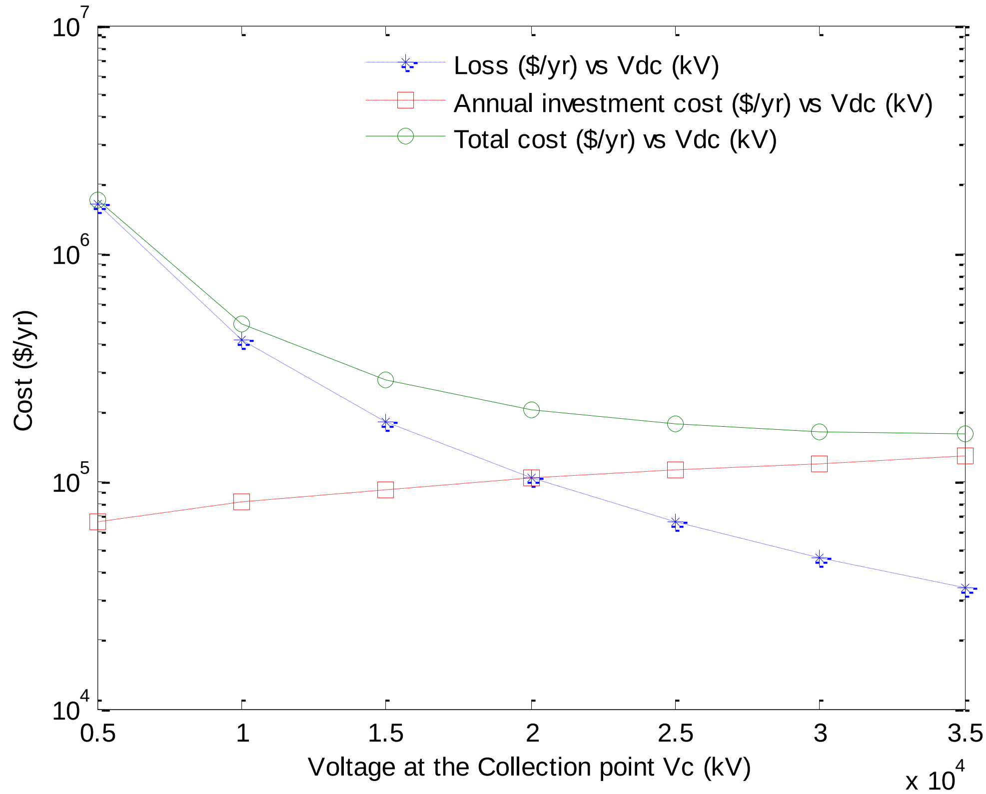


Figure 4.8: Plot of voltage at the main DC bus vs total cost for $m_i$= 10, $n_f$ =2, Pt = 3 MW

Figure 4.8 represents the plot of voltage at the collection point vs. annual investment of the cable and the loss in the transmission cable for different voltage levels. It can be seen that the cost of the transmission cable increases with increase of the voltage level and the losses in the transmission line decrease with increase of the voltage level. The lowest point on the graph indicates that the optimal voltage, which is 35 kV.

In summary, the chapter covers different wind system configurations and the optimal transmission voltage within the wind farm is obtained for each of them. These are example configurations and a similar procedure can be followed to solve for a practical wind farm system. In chapter 5 steady state analysis is performed on the wind system configurations presented in chapter 4 to determine the power loss.

# CHAPTER 5

# STEADY STATE ANALYSIS

## 5.1 Wind Farm Modeling

Performance of a multiphase system under steady state conditions is analyzed using WinIGS-F program. Wind system configurations 1, 4 and 8 are modeled to analyze the system performance. Wind system configuration 1 is shown in figure 5.1. It has an AC grid with nominal frequency transmission throughout the transmission network. In figure 5.2 low frequency transmission i.e. 20 Hz transmission is adapted from the collector substation to the main grid. The program performs power flow analysis of the system together with its ground wire connections. The power flow solution report that is generated by running the models gives the total generated power, total load power and total power losses. The wind system configuration 1 is modeled as shown in figure 5.1. The device parameters used for the models are presented in appendix A.

### 5.1.1 Wind system configuration 1_ model 1

In the system shown in figure 5.1 the wind farm is connected to a transmission line 54 miles long. Wind farm consists of 3 radial feeders with 4 wind turbines on each radial feeder. All the wind turbines are identical and rated 2.7 MW each. A three phase two winding transformer rated 3 MVA is connected to each wind turbine to raise the voltage to 25 kV. The power generated at each wind turbine is collected at the collector substation. A transformer rated 36 MVA with primary voltage of 25 kV and secondary voltage of 115 kV is installed at the collector substation. At the end of the transmission line a three phase constant electric load and a slack generator are connected.

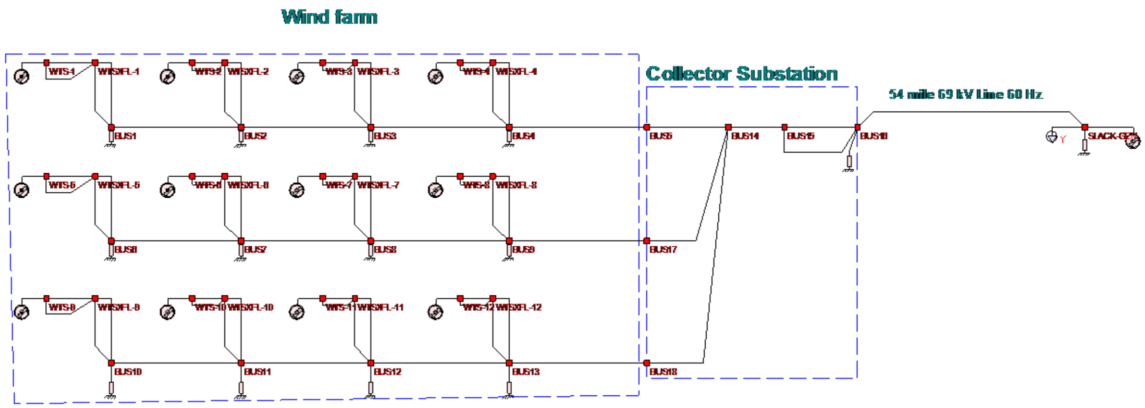


Figure 5.1 Wind system configuration 1 (60 Hz transmission)

Total power loss during transmission is obtained by running the model and it is 1.1925 MW for this case. The power flow solution report showing the total generated power, load power and the total losses is presented in figure A.22.

Table 5.1 Transmission power loss for Wind system configuration 1 (60 Hz transmission)

| Operating voltage (kV) | Transmission length (miles) | Power loss (MW)<br>60Hz transmission |
|---|---|---|
| 69 | 54 | 1.1925 |
| | 100 | 2.1294 |
| 115 | 54 | 0.4435 |
| | 100 | 0.7764 |
| 138 | 54 | 0.3179 |
| | 100 | 0.5454 |

In the table 5.1 the operating voltage, transmission length and power loss during transmission are tabulated. It can be seen that as the operating voltage of the transmission line increases the power loss decreases. This is due to the decrease in the current with the increase in the operating voltage which in turn decreases the $I^2R$ losses. The table 5.1shows the power loss for different operating voltage ranges 69kv, 115 kV and 138 kV. Transmission line lengths of 54 miles and 100 miles are considered in the analysis.

Similarly in figure 5.2 wind system configuration 1 with 20 Hz transmission from the collector substation to the main grid is shown. The dotted line in figure 5.2 represents the 60 Hz transmission line and the solid line represents the 20 Hz transmission line at a rated voltage of 115 kV. Dotted line indicates that the line is not connected. Therefore, the figure 5.2 has 20 Hz transmission line under operation. The total power loss in the low frequency AC transmission system is 0.1405 MW. The modeling results show that the power loss in the low frequency AC transmission line is lower than the power loss in the nominal frequency transmission line.

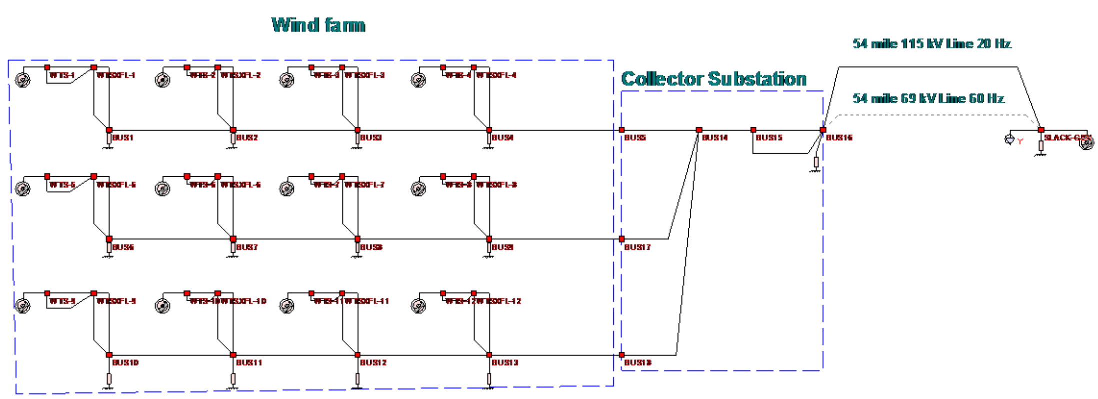


Figure 5.2 Wind system configuration 1 (20 Hz transmission)

### 5.1.2 Wind system configuration 4_ model 2

The wind system configuration 4 is modeled as shown is figure 5.3. It has two small wind farms located at a distance away from each other. This model is similar to a scenario where there are two wind farms in different geographical areas and power is collected at the collector substation and transferred over long distances to the main grid. Under any disturbance to the generation of power in one of the wind farms the other wind farm supplies the power.

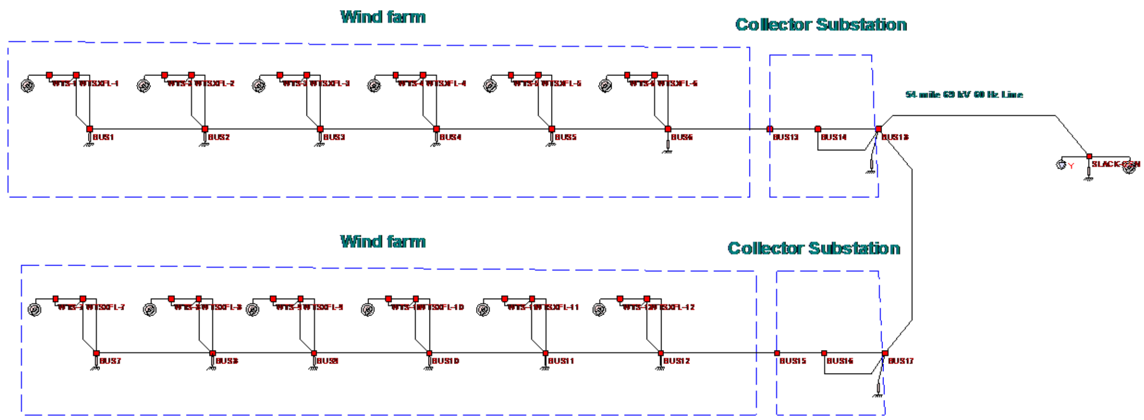


Figure 5.3 Wind system configuration 4 (60 Hz transmission)

Each wind turbine is rated 2.7 MW with 25 kV operating voltage within the wind farm. The operating voltage of the long distance transmission line from the collector substation to the main grid considered here is 69 kV. Different operating voltages are considered as shown in table 5.2 to calculate the total power loss. The power loss in this system is 1.2488 MW.

Table 5.2 Transmission power loss for wind system configuration 4 (60 Hz transmission)

| Operating voltage (kV) | Transmission length (miles) | Power loss (MW) 60 Hz transmission |
|---|---|---|
| 69 | 54 | 1.2488 |
| | 100 | 2.2015 |
| 115 | 54 | 0.5483 |
| | 100 | 0.8718 |
| 138 | 54 | 0.3962 |
| | 100 | 0.6184 |

### 5.1.3 Wind system configuration 8 _ model 3

The wind system configuration 8 is modeled as shown in figure 5.4. A 20 Hz transmission line, 54 miles long and operating at 69 kV is modeled in this case.

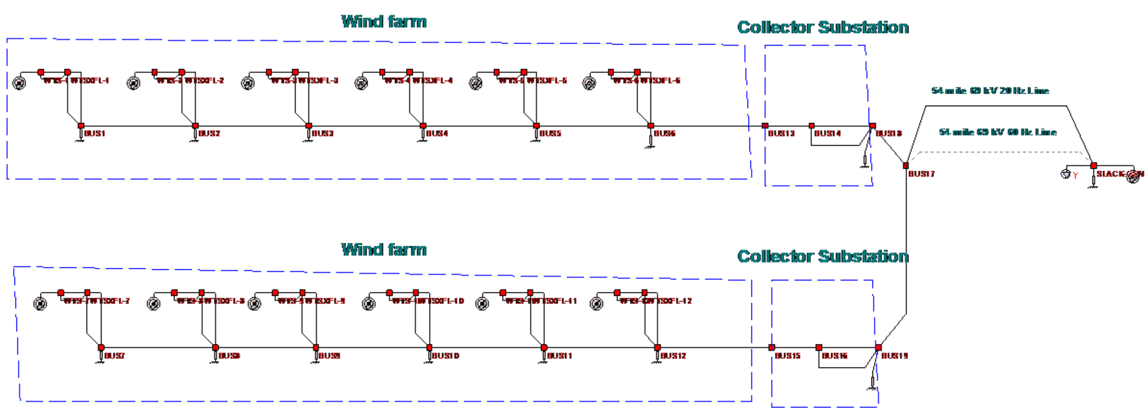


Figure 5.4 Wind system configuration 8 (20Hz transmission)

Table 5.3 shows the power loss for the wind system configuration 8 under different operating voltages and transmission distances. The results show that the loss on a low frequency system is lower compared to nominal frequency transmission. In addition, the transmission line parameters used for 60 Hz transmission can be used for 20 Hz transmission.

Table 5.3 Transmission power loss for wind system configuration 8 (20 Hz transmission)

| Operating voltage (kV) | Transmission length (miles) | Power loss (MW) 20 Hz transmission |
|---|---|---|
| 69 | 54 | 0.3395 |
| | 100 | 0.3398 |
| 115 | 54 | 0.1586 |
| | 100 | 0.1589 |
| 138 | 54 | 0.1281 |
| | 100 | 0.1283 |

To summarize, the chapter consists of different wind system configurations modeled to perform steady state analysis. The power flow report which gives the total generated power, total load power and the total power loss of the system is presented in figure A.22, figure A.23, figure A.24 and figure A.25. The Wind system configuration 1 is a system with nominal frequency i.e. 60 Hz transmission as shown in figure 5.1 and figure 5.2 represents a 20 Hz transmission system. These two models are identical except for the transmission part. The models shown in figure 5.3 and figure 5.4 are a special scenario where two different wind farms are interconnected via a transmission line to supply the power generated to the main grid.

# CHAPTER 6

# CONCLUSIONS AND FUTURE WORK

Geographical locations that are suitable for wind farm development are in remote locations far from the main transmission grid and major load centers. In these cases, the transmission of wind power to the main grid is a major expenditure. The potential benefit of the LFAC technology presented in this study is the reduction in the cost of the transmission system. This makes the economics of the wind energy favorable and increases the penetration of wind power into the system.

LFAC technology is used for transmission from the collector substation to the main power grid. The thesis presents alternate topologies suitable for various geographical locations and configurations of the wind farm. The optimal operating voltage of the transmission lines within the wind farm is calculated for all the cases. The optimal voltage is computed considering the cost of the cable, converter equipment and the power loss due to transmission.

The preliminary study results show that higher the operating voltage lower will be the transmission losses and with the increase of the transmission distance the transmission losses on the line increase. The results obtained by modeling the wind system configurations point towards higher transmission losses in 60 Hz transmission compared to 20 Hz transmission.

Future development of the LFAC transmission system would require more work to improve the overall system performance. LFAC transmission will allow the economical development of storage systems, such as hydro or pumped hydro which needs to be investigated further. Transient stability analysis needs to be done to study the stability of the power system under contingencies and to determine the transient discharge/charge rates of the storage scheme and optimize its operation. Further, investigation of power transfer capability index in terms of MW would give the amount of power transfer that can be done over and above the operating conditions before violating constraints.

# APPENDIX A

## DEVICE MODELS AND LINE CONFIGURATIONS

This Appendix presents the parameters of the system used in chapter 5. The single line diagram of the system is shown in Figure 5.1. It represents wind system configuration 1 where the wind farm is connected to a transmission line 54 miles long. Wind farm consists of 3 radial feeders with 4 wind turbines on each radial feeder. Models of the generator, three phase transformer at the wind turbine and the collector substation, cable models and parameters of the transmission cable are shown in the figures below.

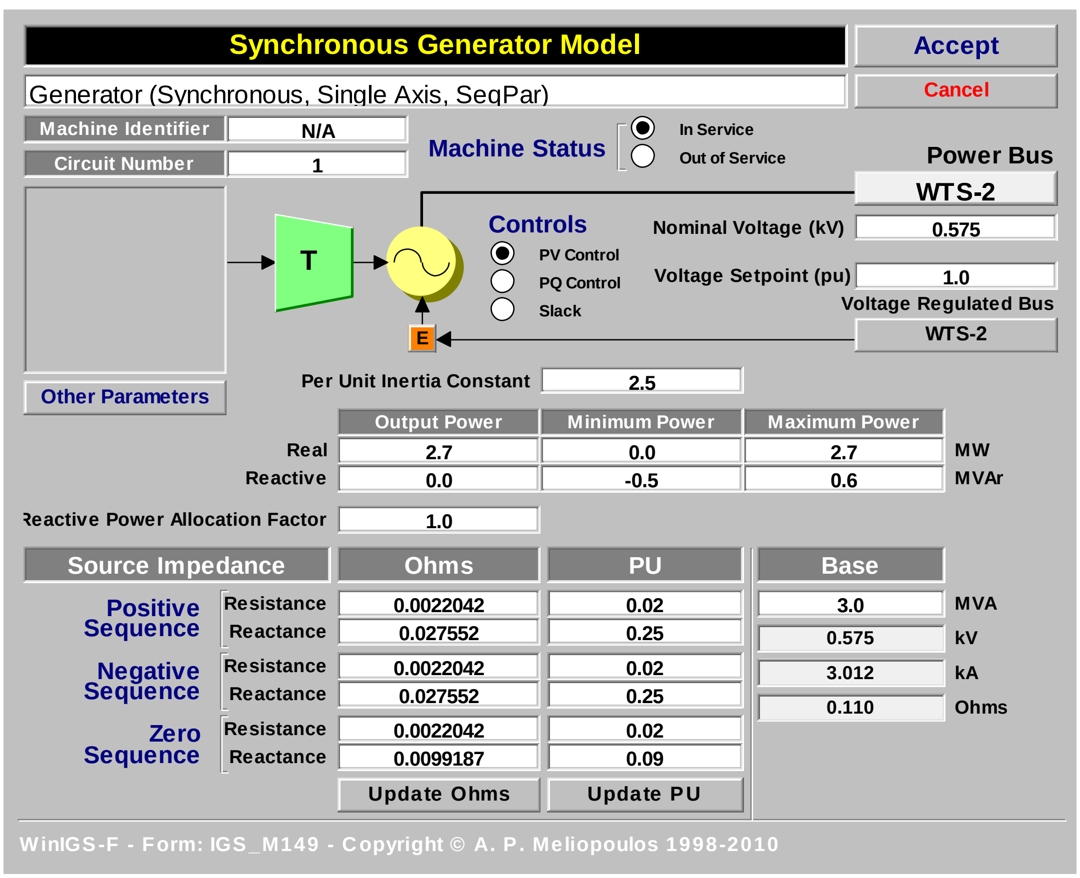


Figure A.1 Generator parameters for WinIGS-F model 1

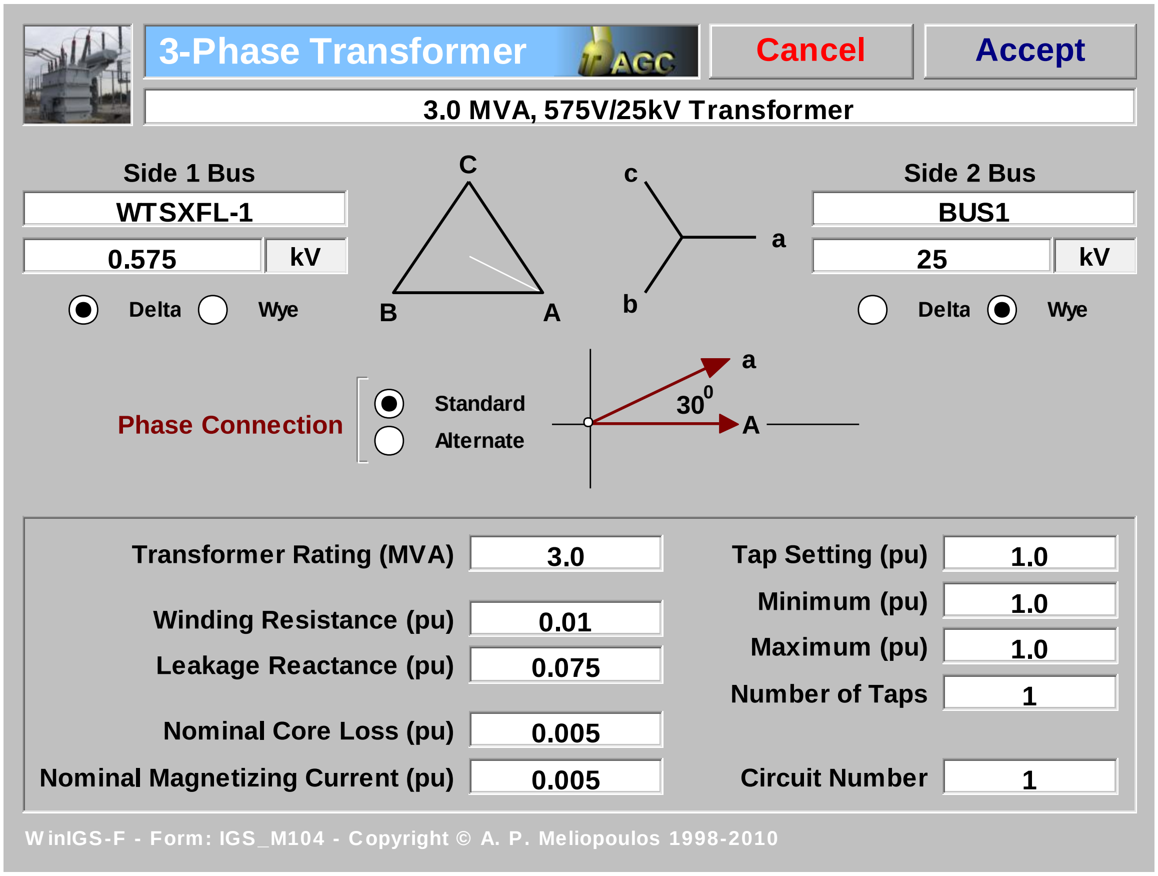


Figure A.2 Parameters of three phase step up transformer at the wind turbine system

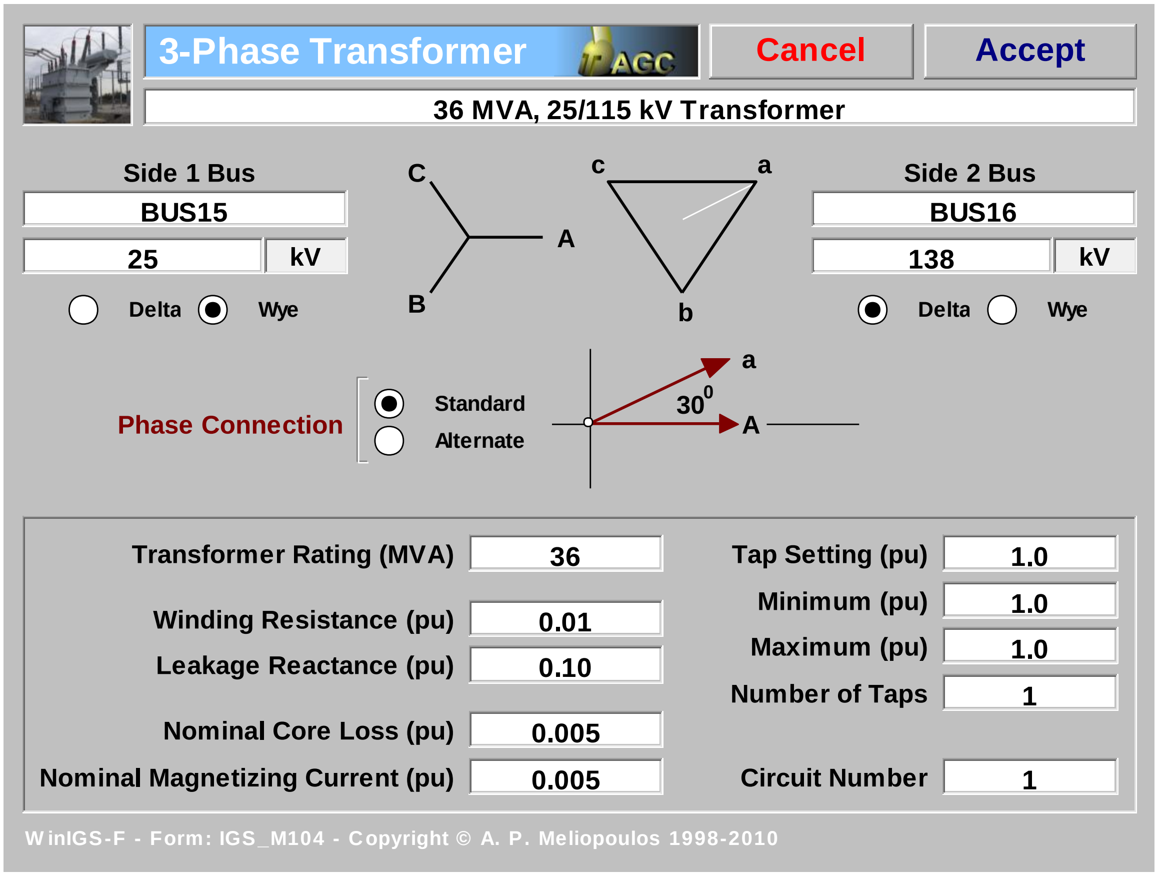


Figure A.3 Parameters of three phase transformer at the collector substation

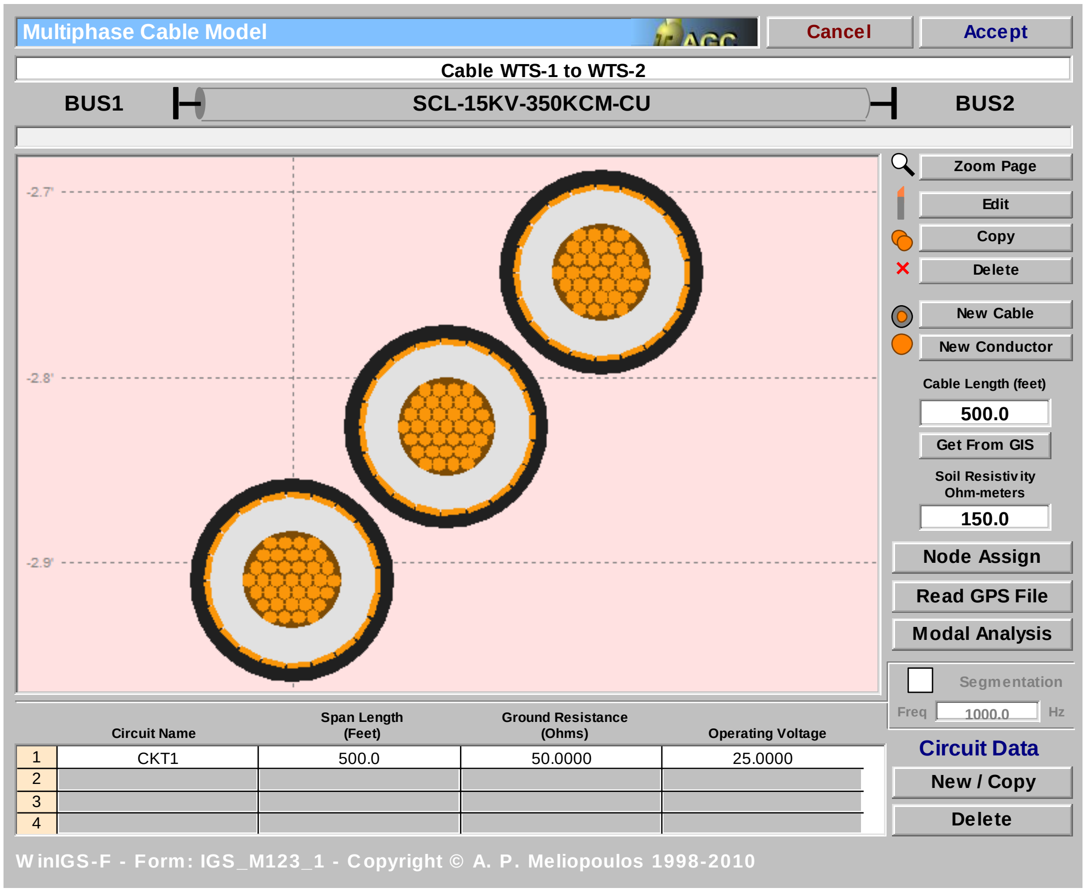


Figure A.4 Cable model for WinIGS-F model 1

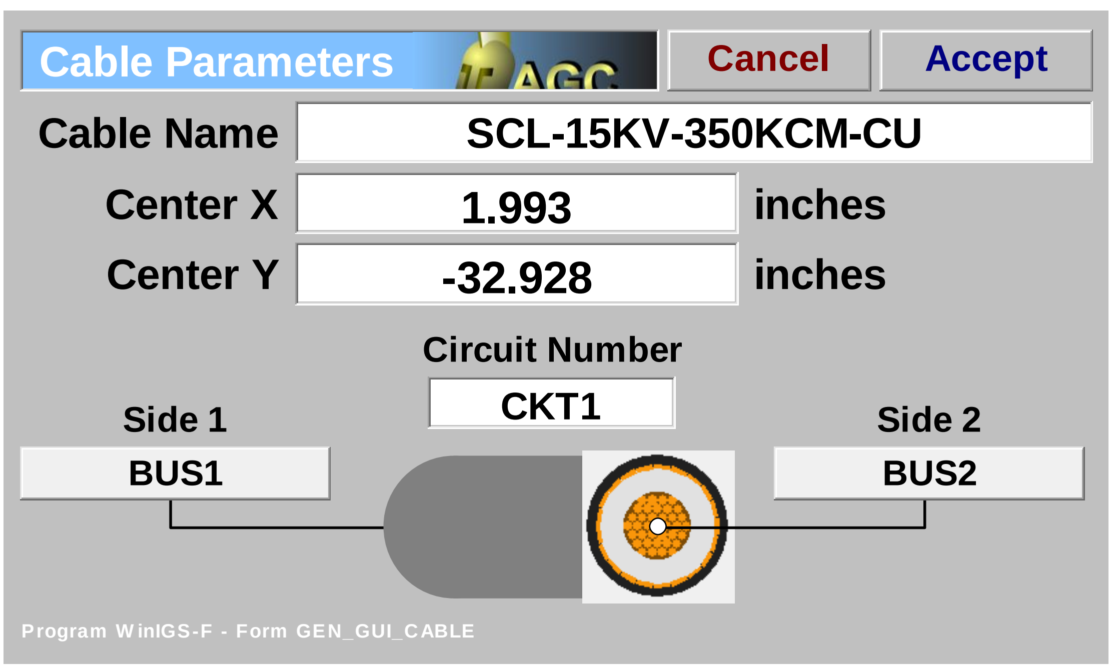


Figure A.5 Cable parameters

Three phase overhead transmission lines with different operating voltages and transmission distances are shown in figures A.6, A.7, A.8, A.9, A.10 and A.11. The transmission lengths considered are 54 miles and 100 miles. Different operating voltages considered are 69 kV, 115 kV and 138 kV.

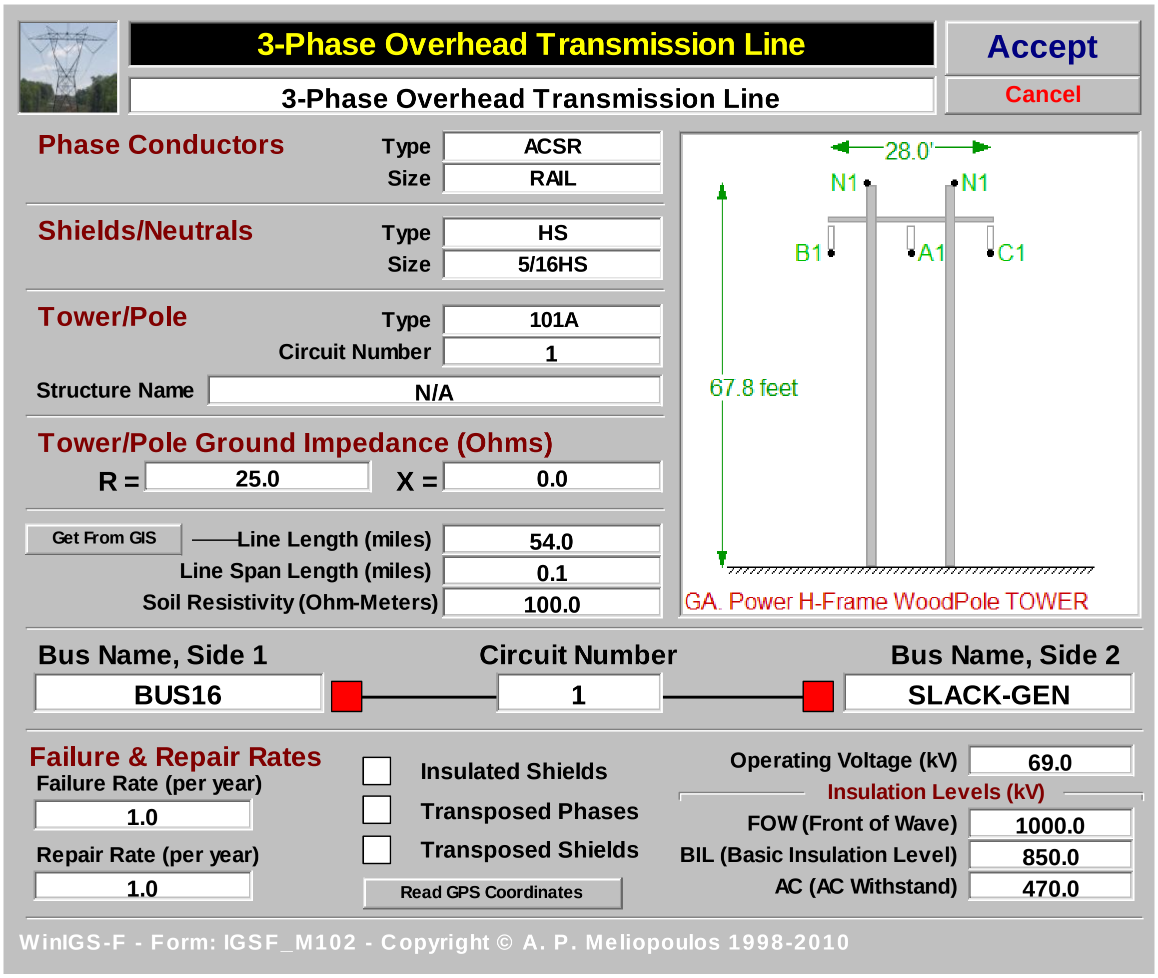


Figure A.6 Parameters of three phase overhead transmission line (length = 54 mi, operating voltage = 69 kV)

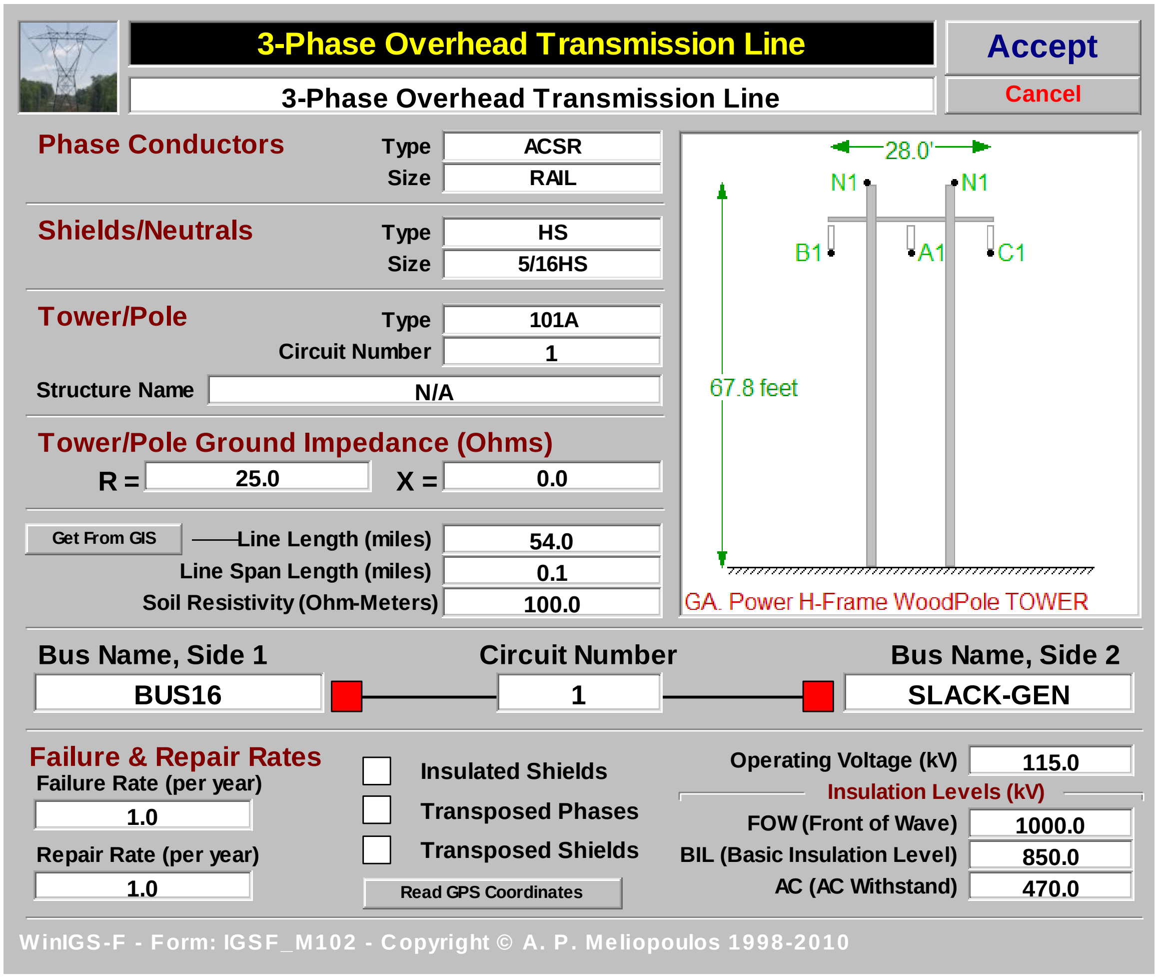


Figure A.7 Parameters of three phase overhead transmission line (length = 54 mi, operating voltage = 115 kV)

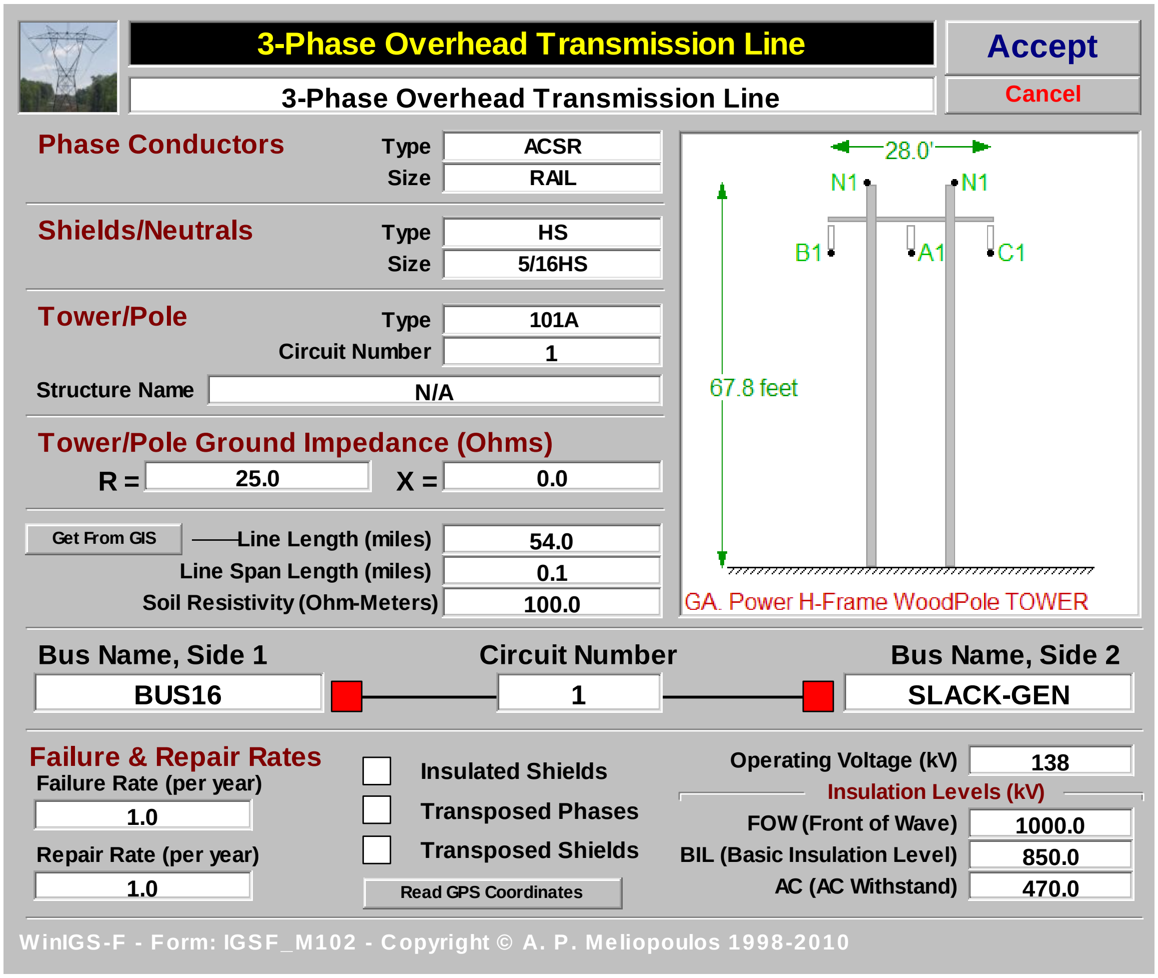


Figure A.8 Parameters of three phase overhead transmission line (length = 54 mi, operating voltage = 138 kV)

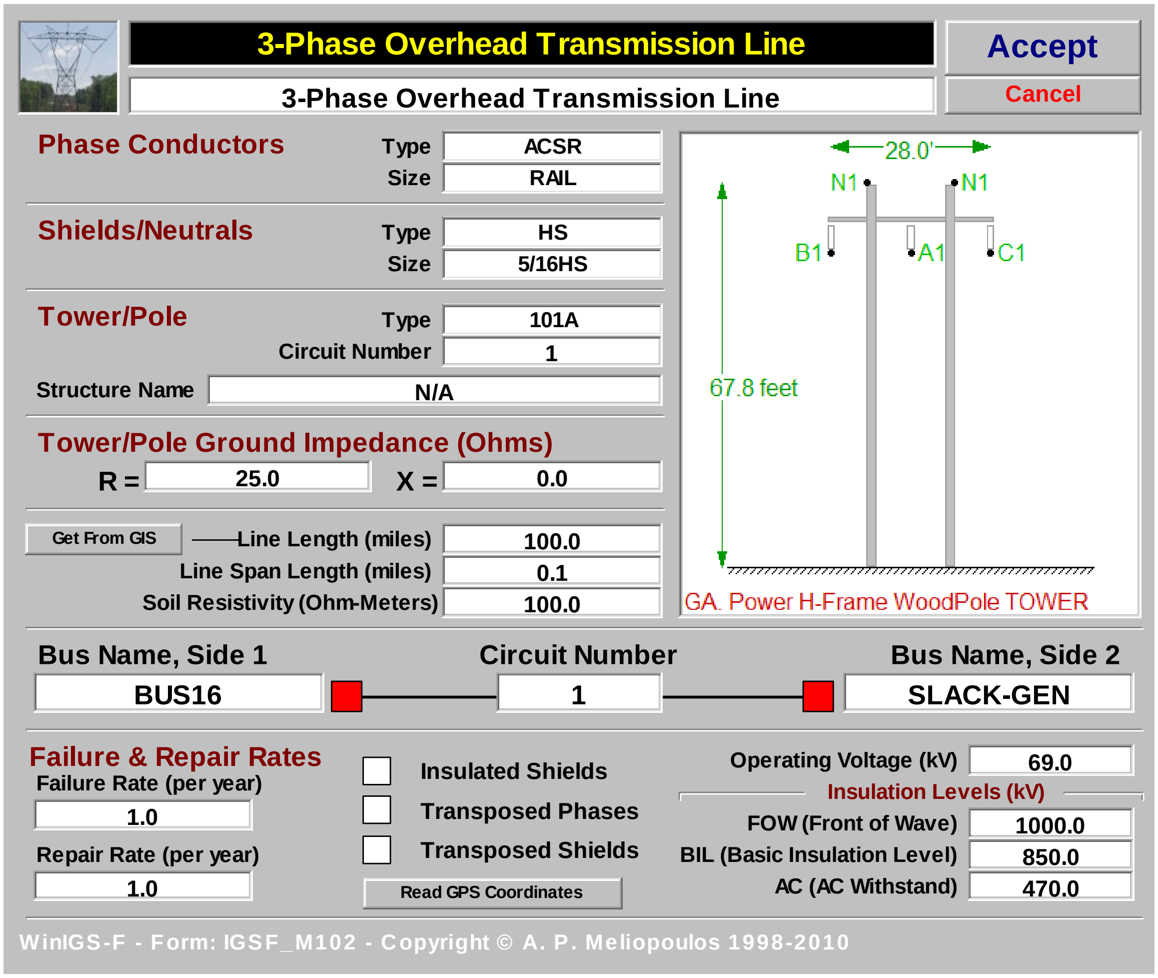


Figure A.9 Parameters of three phase overhead transmission line (length = 100 mi, operating voltage = 69 kV)

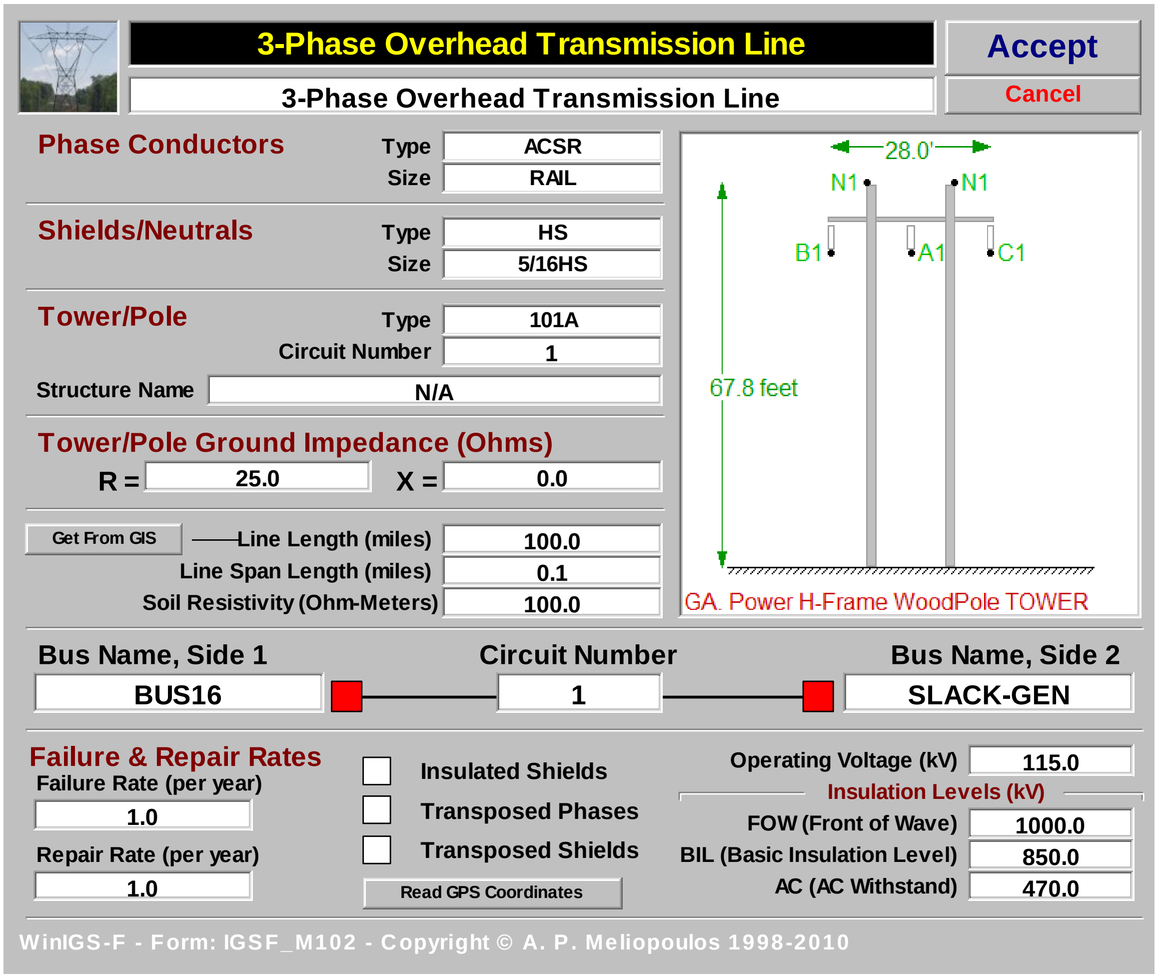


Figure A.10 Parameters of three phase overhead transmission line (length = 100 mi, operating voltage = 115 kV)

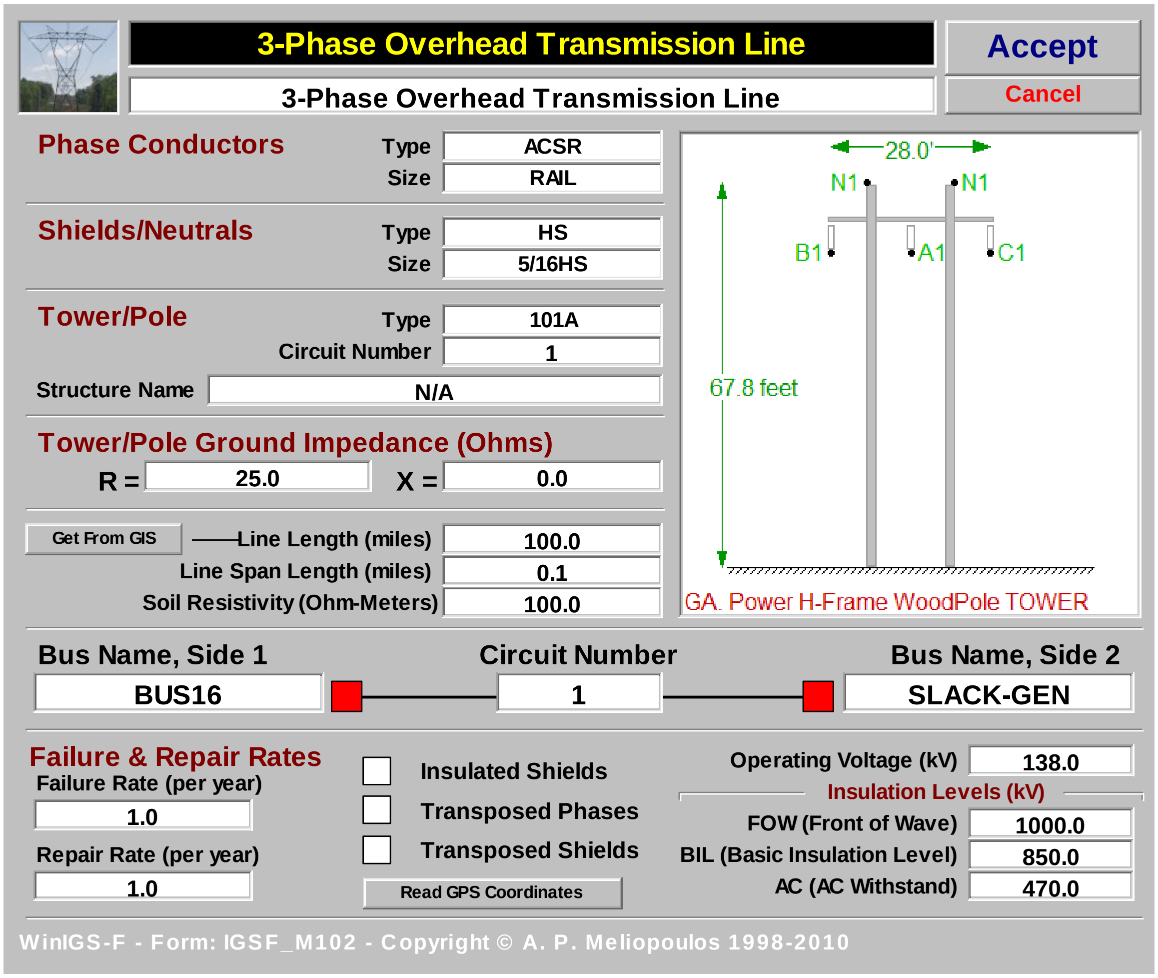


Figure A.11 Parameters of three phase overhead transmission line (length = 100 mi, operating voltage = 138 kV)

Parameters of a constant power three phase load of 50 MW is shown in figure A.12.

Figure A.13 represents the model of the slack generator.

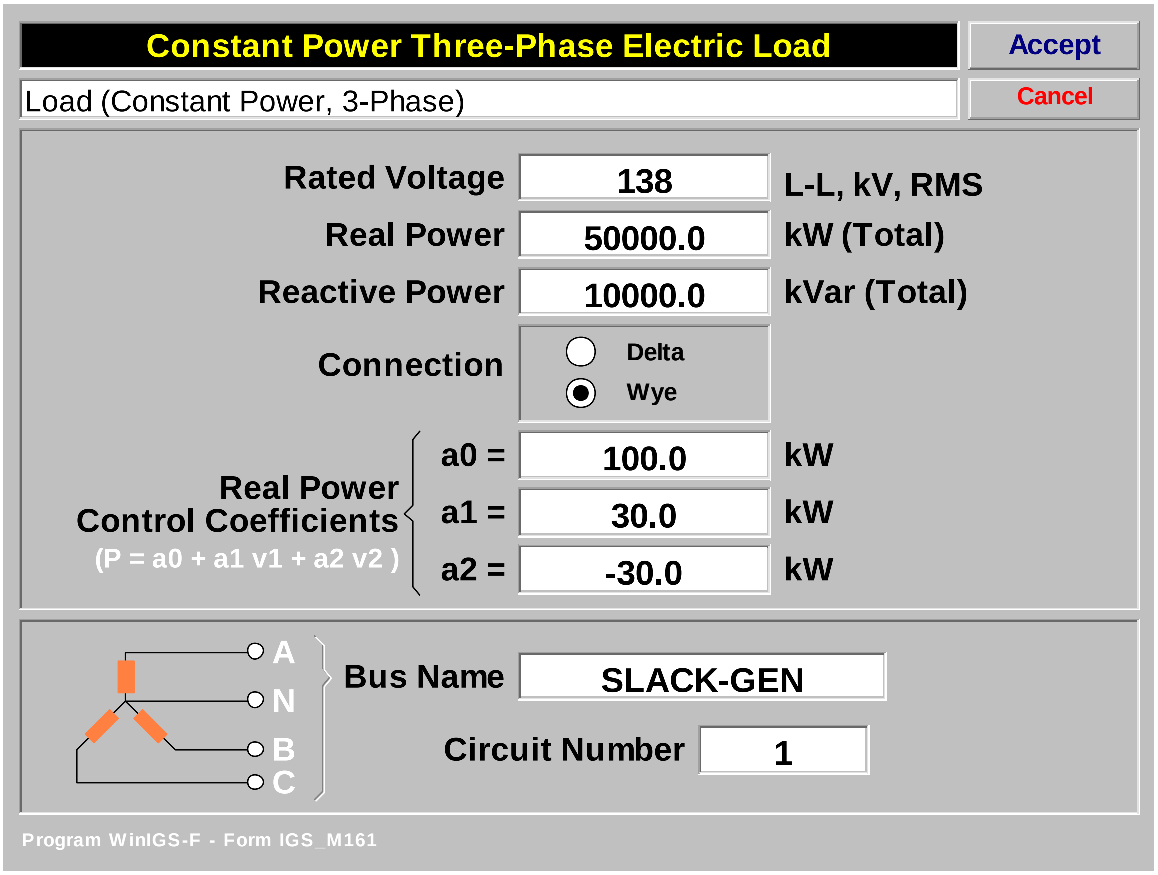


Figure A.12 Parameters of Constant Power three-phase Electric load

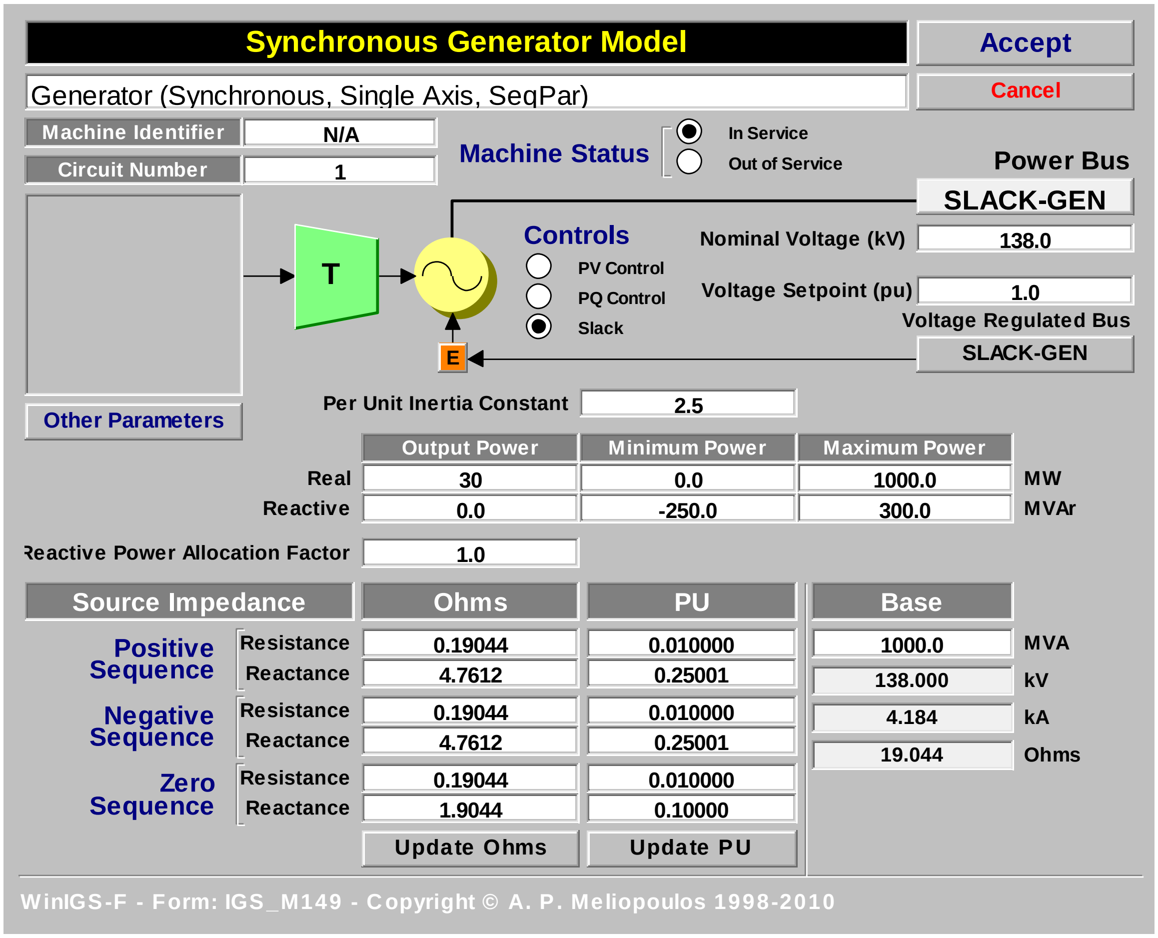


Figure A.13 Parameters of the slack generator

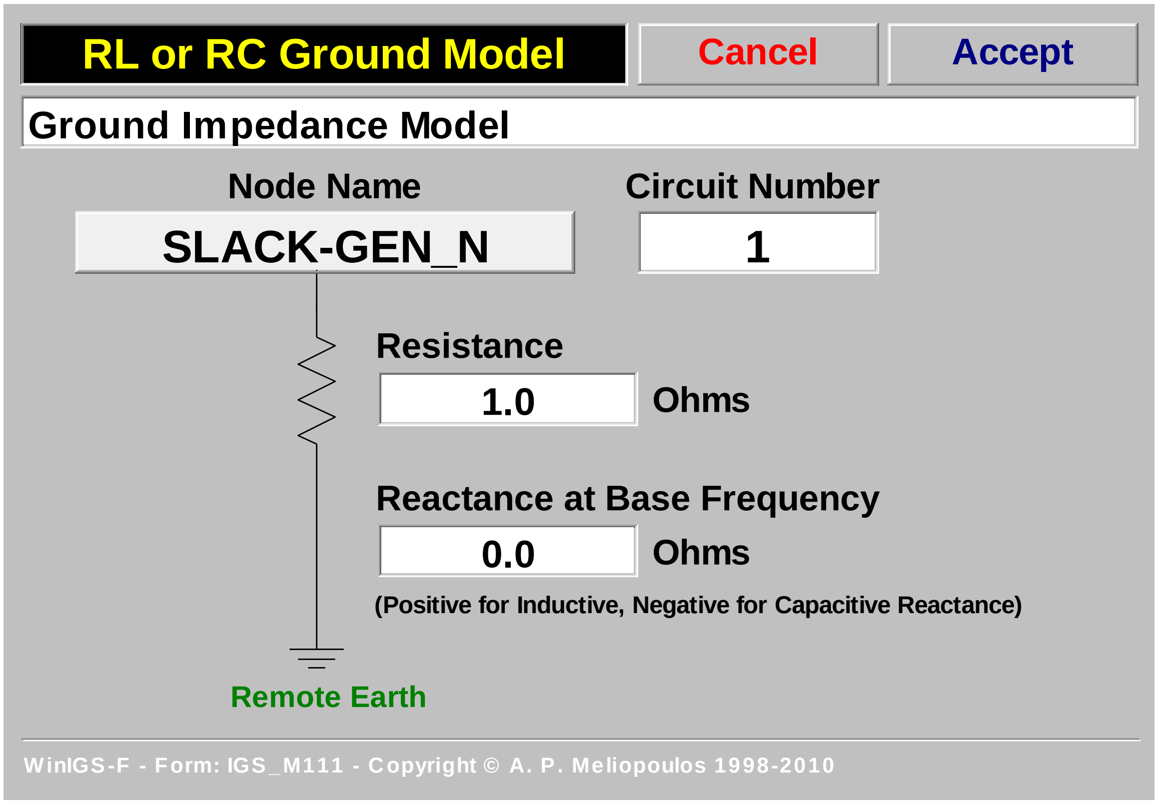


Figure A.14 Parameters of the ground impedance model

Figure A.15 shows the parameters of a 20 Hz transmission line operating at 138 kV. The transmission system from the collector substation to the main power grid in the wind system configuration 8 shown in figure 5.4 uses the parameters shown in figure A.15 for 20 Hz transmission.

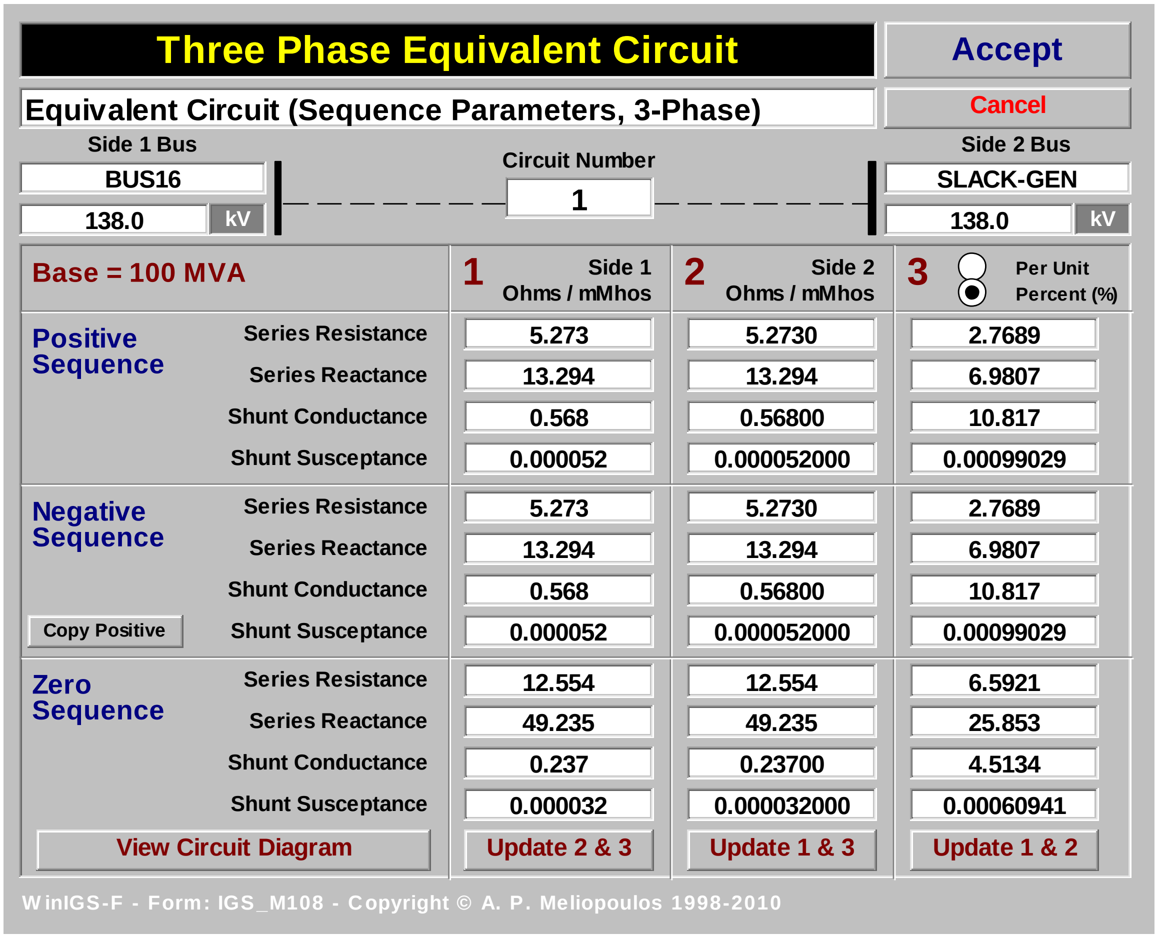


Figure A.15 Parameters of the 20 Hz transmission line operating at 138 kV

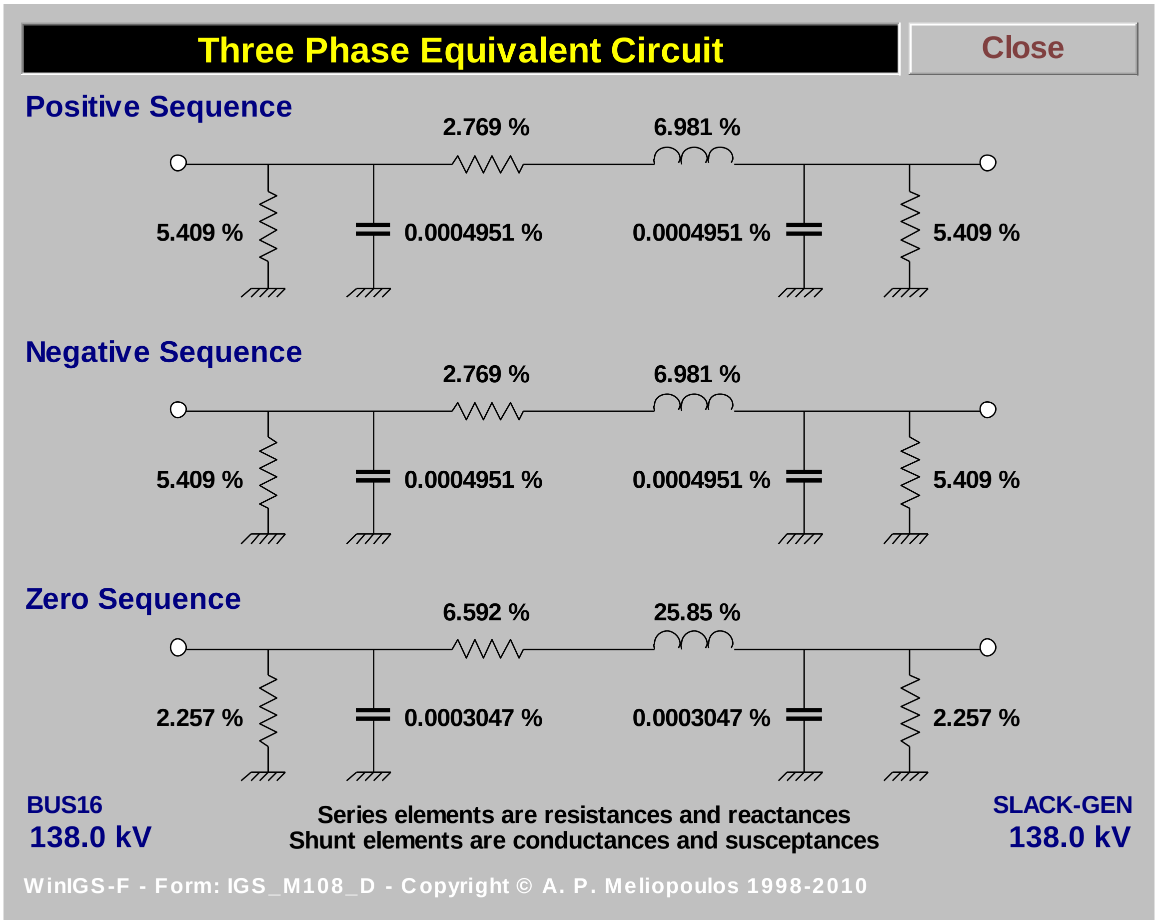


Figure A.16 Three phase equivalent circuit of the 20 Hz transmission

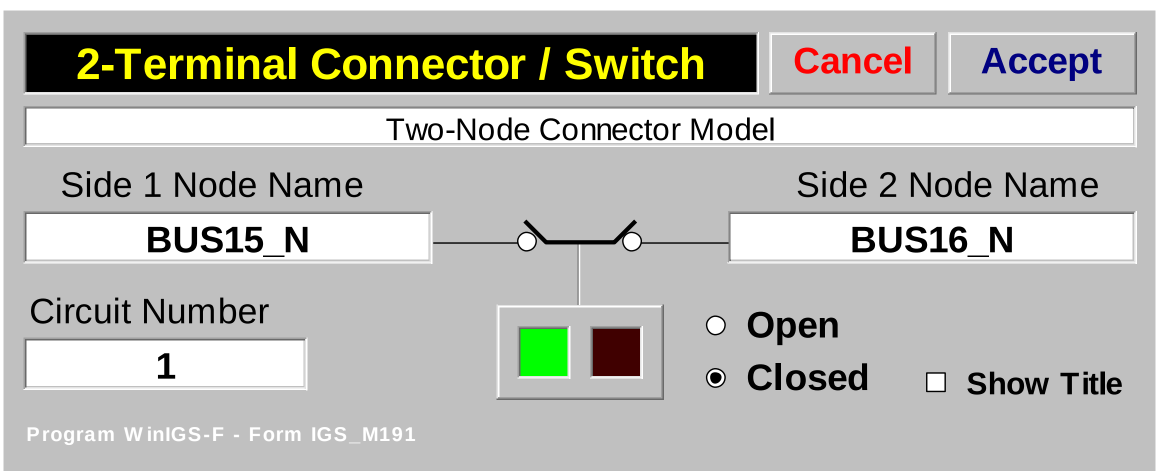


Figure A.17 2-Terminal connector model

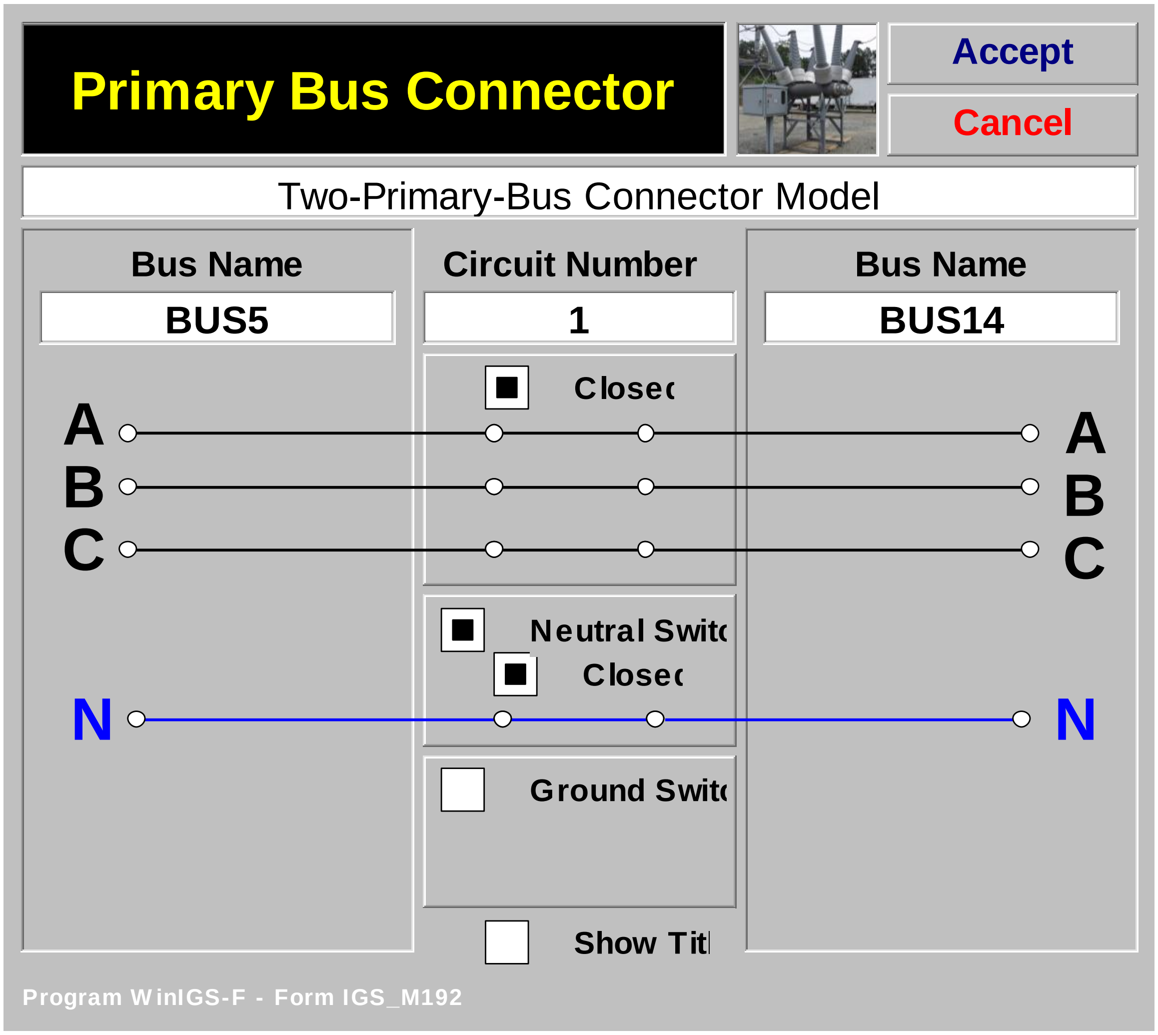


Figure A.18 Model for the Two-Primary-Bus Connector Model

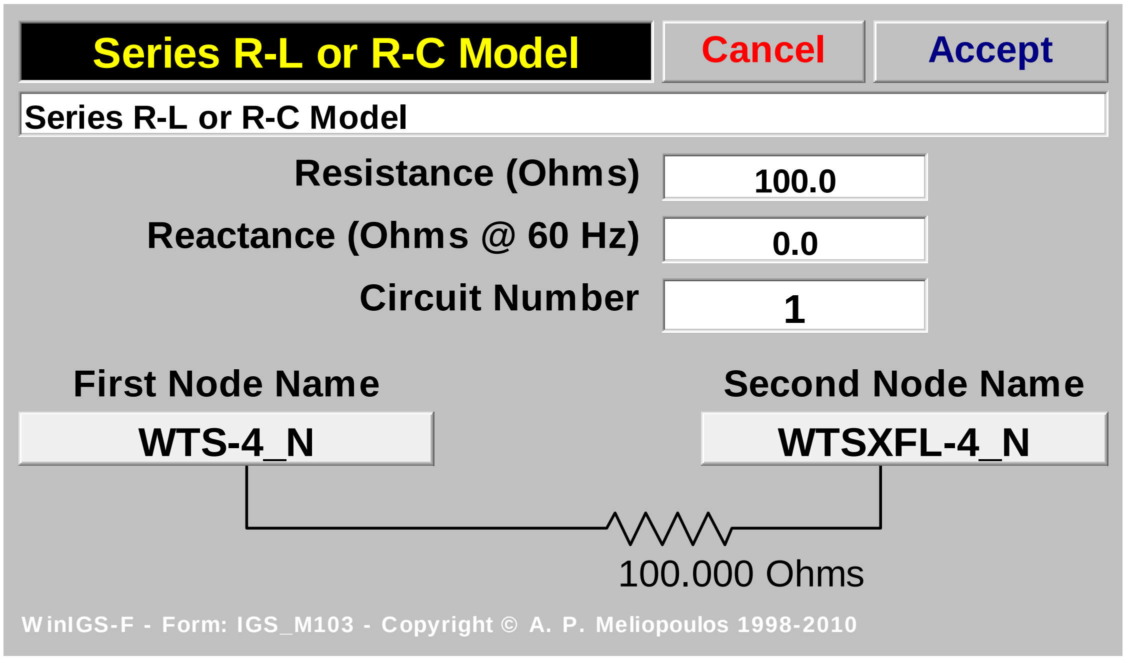


Figure A.19 Parameters of the Series R model

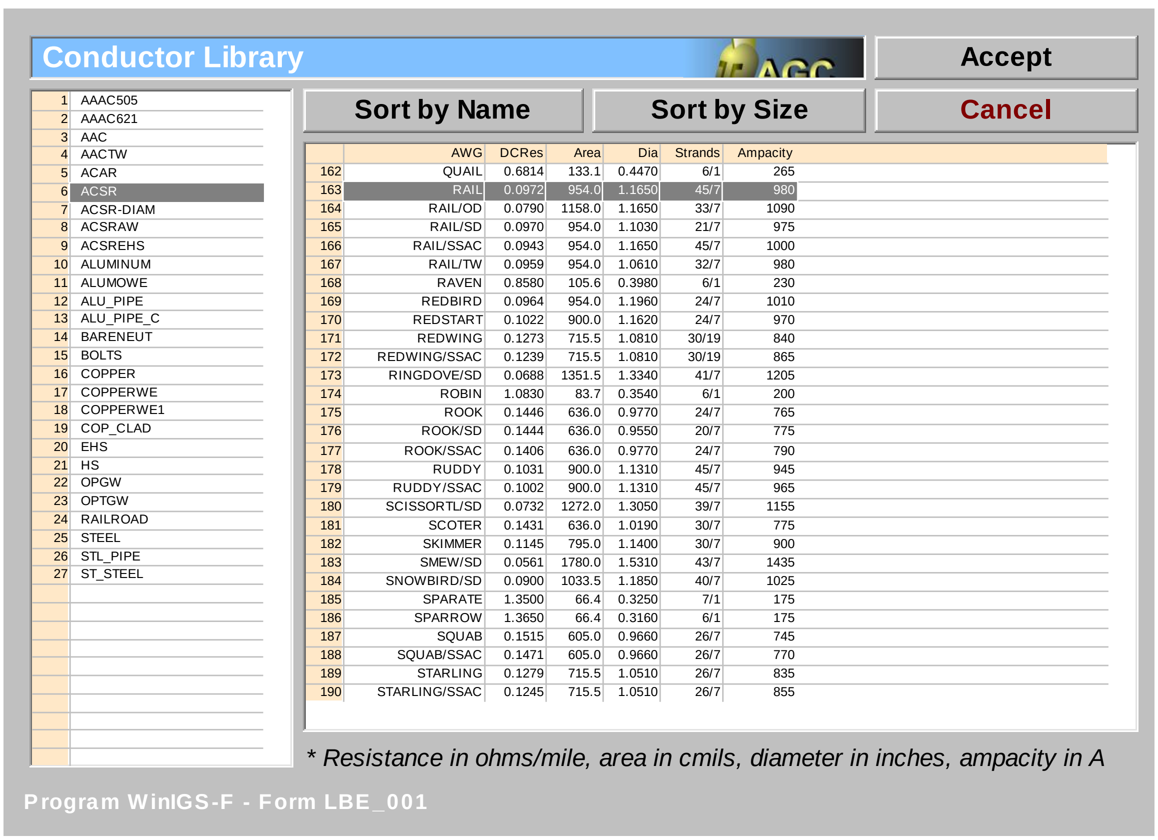


Figure A.20 Conductor library

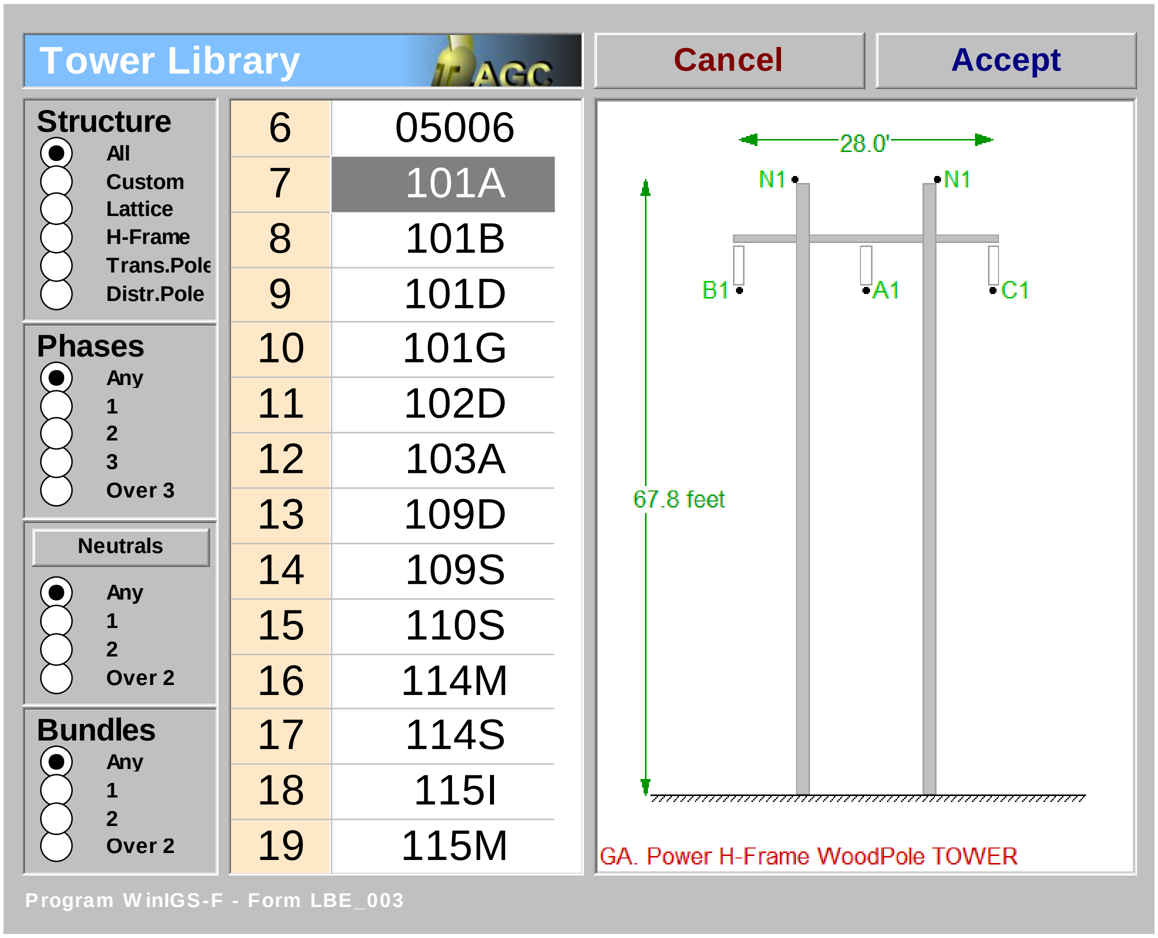


Figure A.21 Tower library

The power flow solution reports for different wind system configurations discussed in chapter 5 are shown in figures A.22, A.23, A.24, and A.25. The solution report shows the total power generation, load power and the total power loss in MW. The maximum and minimum PU voltages are also one of the outputs.

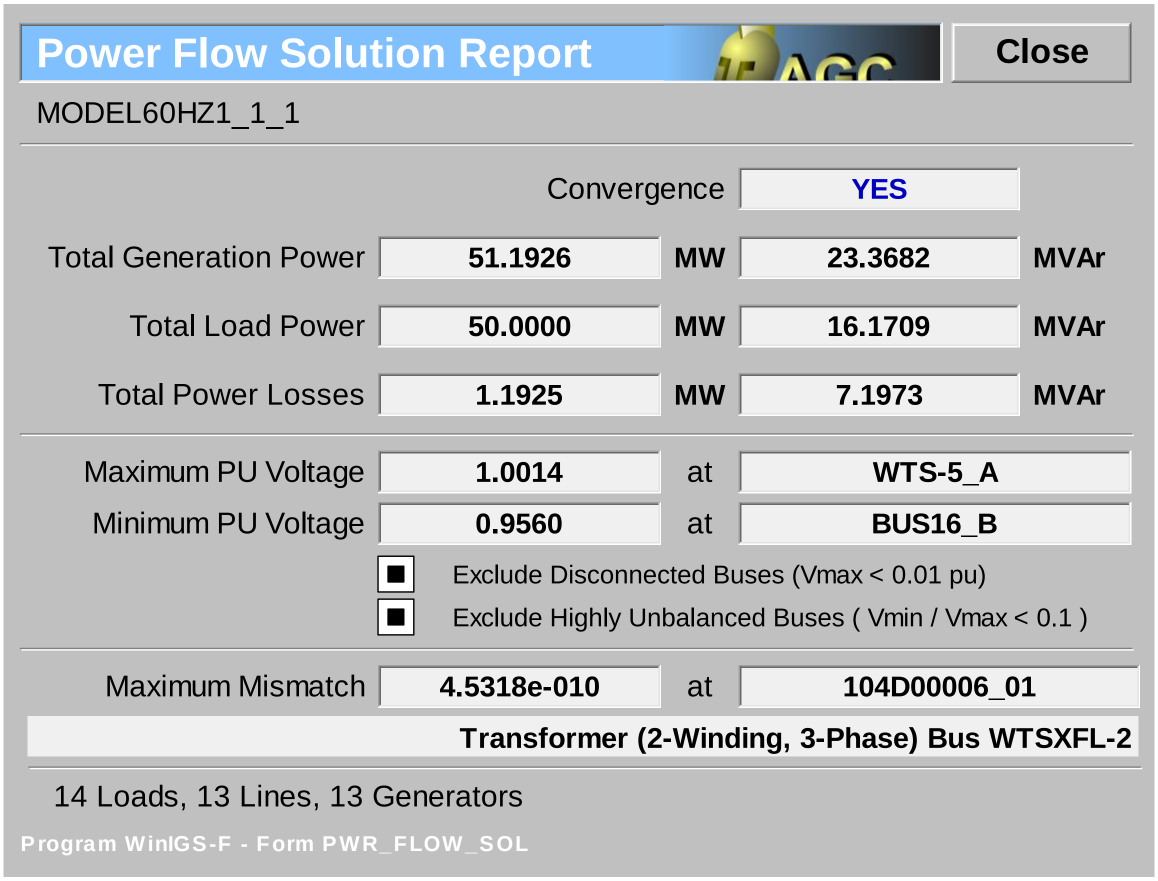


Figure A.22 Power flow solution report for wind system configuration 1 (60 Hz transmission)

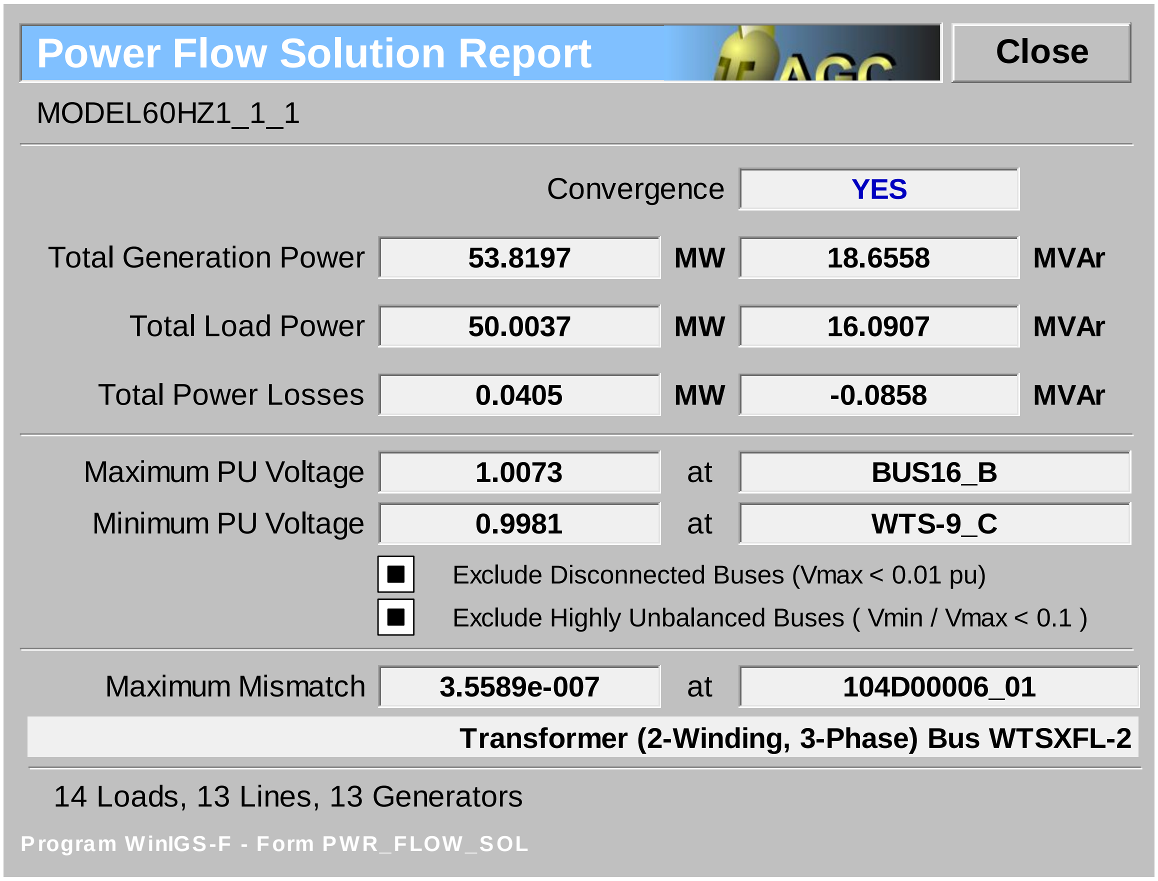


Figure A.23 Power flow solution report for wind system configuration 1 (20 Hz transmission)

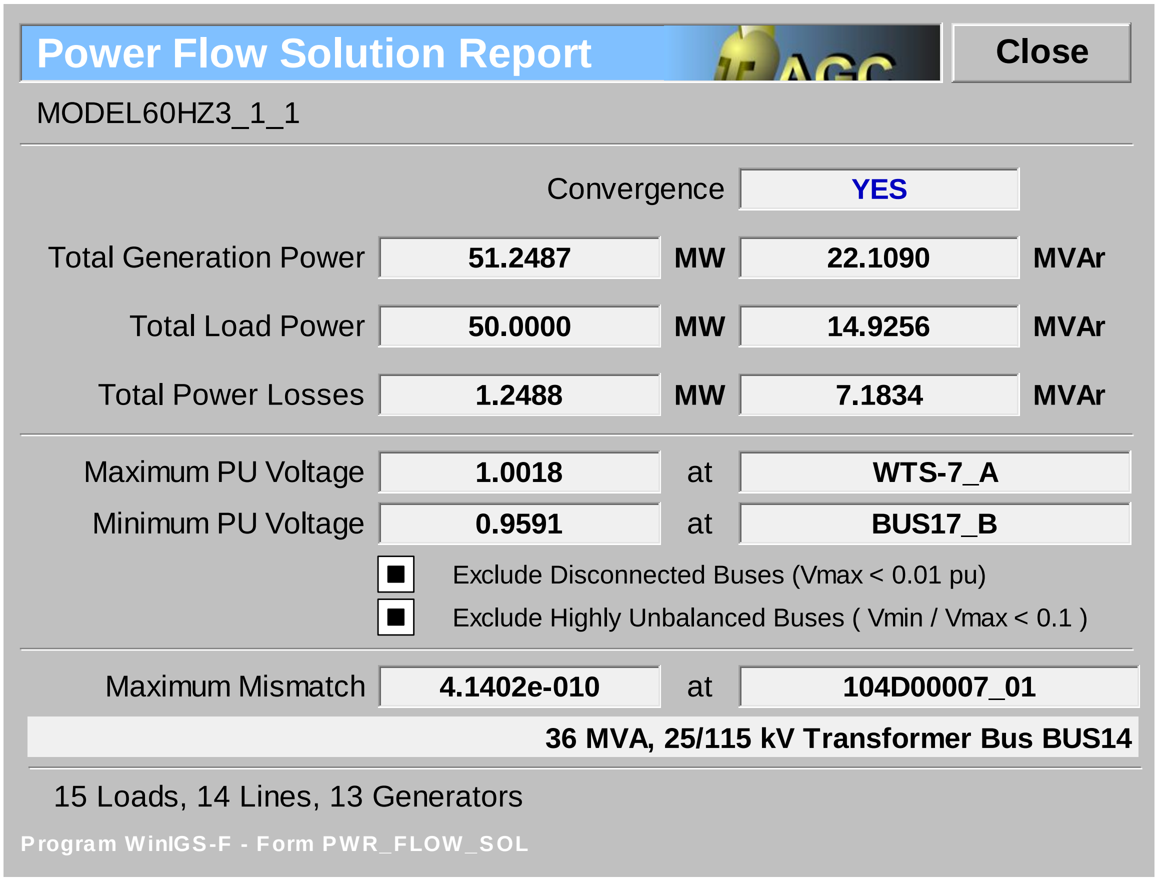


Figure A.24 Power flow solution report for wind system configuration 4 (60 Hz transmission)

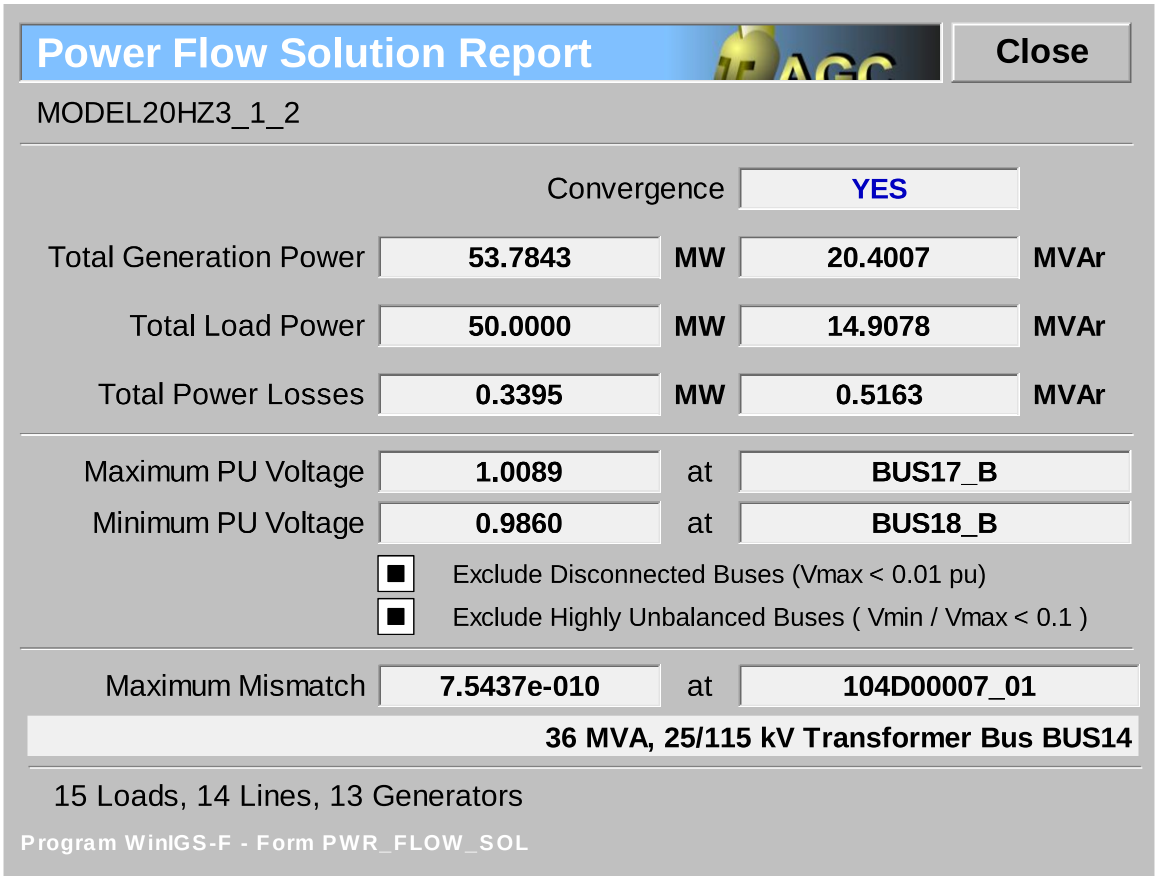


Figure A.25 Power flow solution report for wind system configuration 8 (20 Hz transmission)

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