Analysis and design of connection between solar farm and IEEE 9 bus system

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Xin Li
Department of Electrical Information
Shandong University of Science and Technology (Jinan)
Jinan, China
19862196889@163.com

Kunheng Li
Department of Electrical Information
Shandong University of Science and Technology (Jinan)
Jinan, China
lkh188204@163.com

Abstract*—This paper designs a connection of a new large-scale solar farm (160 MW) to an existing 230 kV system (based on the IEEE 9 bus system). Regarding the choice of connecting the solar farm to Bus, this paper respectively gives the analysis of Bus5, Bus6 and Bus8, and draws the conclusion that connecting Bus5 is the best choice. When designing the transmission line, this paper gives the shortcomings of tower type B and tower type C, analyzes the reasons for choosing tower type A, and analyzes the various parameters of 5 different conductors. The best conductor choice is 16.33 mm wire, the best conductor bundling option is bundling spacer – 2 conductors. Then, this paper used PowerWorld to simulate the circuit diagram of the IEEE 9 bus system, and carried out power flow analysis and system safety analysis on the power system. It is recommended to connect the transmission line in parallel between Bus5 and Bus7 and between Bus4 and Bus5 to enhance the safety and stability of the system. When any one of the transmission lines is disconnected, the remaining transmission lines will not overcurrent and can work safely. Finally, this paper analyzes the total cost of the design from three aspects: new transmission lines, parallel conductors of old transmission lines, parallel capacitor and inductor, and calculates the total cost is $1,405,398,400.

Keywords*—*IEEE 9 bus system, Parameter calculation, Power flow analysis, Total cost

I. Introduction

IEEE 9 Bus System is a common power analysis system, which is often used to analyze and implement new transmission ideas and concepts [1]. The system consists of loads, transmission lines and generators [2]. After knowing the distance between the solar farm and three bus, three tower type parameters, and five wire parameters, this paper will design a connection of a new large-scale solar farm (160 MW) to an existing 230 kV system (based on the IEEE 9 bus system). The design content includes selecting the appropriate conductor type, bunding, tower type, phase spacing, and using a long-distance model to analyze the relationship between input parameters and output parameters. At the same time, a power flow analysis will be performed on the system to ensure that there is no line overload, and the unit value of all bus voltages cannot exceed the specified range (0.95 to 1.05 pu). In addition, this paper will study and improve the safety of the power system to ensure that if one line fails, the remaining lines can still operate normally without being overloaded. Finally, this paper will determine the cost of the improved connection scheme, which includes the cost of all transmission lines and the cost of all additional equipment added to the network.

II. Parameter analysis and model selection

A. Model and various parameters

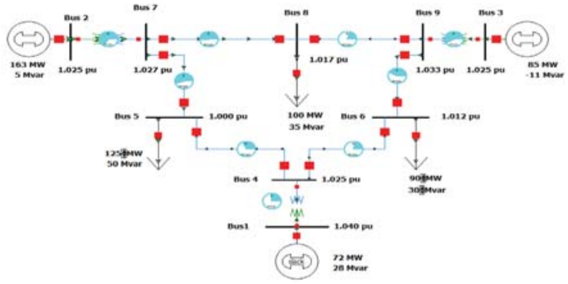

Fig.1. IEEE 9 Bus System

Fig.1 is the simulation panorama of the IEEE 9 Bus System to be analyzed in the following part of this paper.

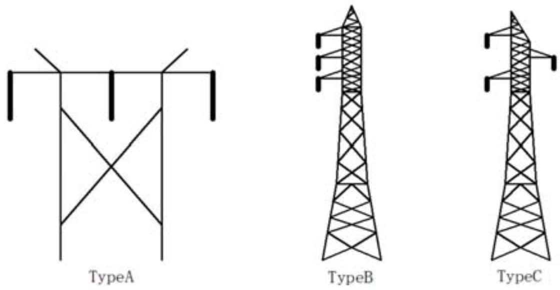

Fig.2. Tower type

Fig.2 shows the three tower diagrams of the IEEE 9 Bus System to be considered in the following part of this paper. In addition, the loads on buses 5 and 6 vary throughout the day. In the middle of the day (when solar is at its peak these loads are): Load 5 - 125MW, 50MVAr; Load6 - 90MW, 30MVAr. In the evening, around 6pm: Load 5 - 225MW, 50MVAr: Load 6-135MW, 45MVAr.

B. Bus selection

The following TABLE I will give the distance from each bus to solar farm, and analyze how to choose a suitable bus.

TABLE I The distance between different bus and solar farm

Connectable bus	Bus5	Bus6	Bus8
Distance	25km	300km	150km

(1) Bus5: Solar farm is the shortest distance from Bus5, it costs the least to set up a transmission line, and the voltage pu value of bus 5 is lower, the voltage rise range is larger. After connection, all parts of the power grid work normally. Fig.3 is a diagram of the power system when the bus 5 is connected.

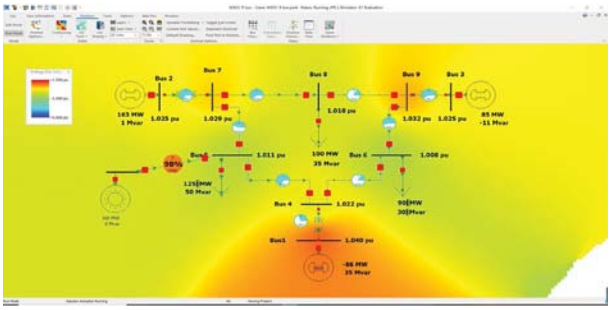

Fig.3. Connection Bus5

(2) Bus6: The solar farm is the farthest from bus 6, so the wiring cost is too high. Connecting the solar farm will make bus 6 and 10 voltage too high. Fig.4 is a diagram of the power system when the bus 6 is connected.

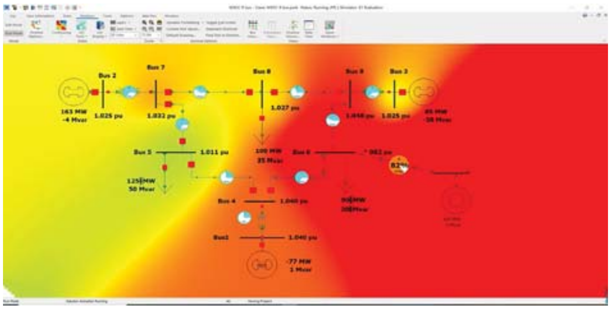

Fig.4. Connection Bus6

(3) Bus8: When the solar farm is connected to bus 8, the transmission line connecting bus 7 and bus 5 will be directly over-current 113%, The other two transmission lines are close to over-current. Fig.5 is a diagram of the power system when the bus 8 is connected.

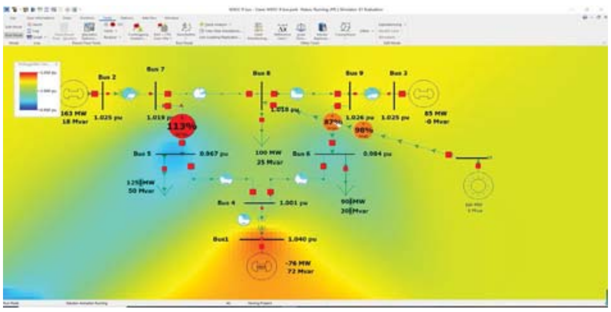

Fig.5. Connection Bus8

The conclusion is that Bus5 is the most suitable bus to connect.

C. Transmission line design

Step1 Calculation of transmission current

If $power\ factor = 1$, the apparent power S is:

$$S = \frac{160MW}{1} = 160\text{MVA}$$

The apparent power of each phase of a three-phase system S_{per} is:

$$S_{per} = \frac{S}{3} = 53.3\text{MVA}$$

Because $\text{U} = 230\text{KV}$, the current I is:

$$\text{I} = \frac{S_{per}}{\frac{\text{U}}{\sqrt{3}}} = 401.4A$$

Step2 Analyze why summer is the extreme case of selecting conductor

When selecting the conductor, because the temperature in summer is higher than that in winter, the overheat resistance will increase due to the increase of temperature, and the transmission of current will be blocked. Therefore, the higher the temperature is, the smaller the current carrying capacity of the conductor will be. Therefore, take summer as an extreme case to ensure that the maximum current of the conductor is not overloaded when the current carrying capacity is small.

Step3 Analyze and determine the wire

TABLE II BUNDLING PATTERN AND INSTALLATION COST

Conductor bundling options	Bundle pattern	Line installation cost (including bundling spacers)
No bundling (1 conductor)	N/A	$30,000 per km
Bundling spacer-2 conductors,22cm	Horizontal, 22cm spacing	$35,000 per km
Bundling spacer-3 conductors,21cm	Triangle, 21cm sides	$40,000 per km
Bundling spacer-4 conductors,25cm	Square, 25cm sides	$45,000 per km

(1) AAC 9.0 mm diameter conductor analysis

The maximum DC resistance at 20°C of 9.0 mm diameter can be found through [3], and the resistance value R of a bundle of transmission lines is 0.579 Ω / km. The maximum current value corresponding to 9.0 mm diameter and current rating (summer, no wind) is 110A by searching the TABLE II and TABLE III that can be passed by the wire. It is concluded that this kind of wire needs at least four same wires in parallel, so that the maximum current reaches 440A. Finally, the resistance value R_1 of four parallel wires can be calculated:

$$R_1 = 0.14475\Omega/\text{km}$$

In extreme case, the utilization rate of conductor is 91.2%.

(2) AAC 16.3 mm diameter conductor analysis

The maximum DC resistance at 20°C of 16.3 mm diameter can be found through [3], and the resistance value R of a bundle of transmission lines is 0.183 Ω / km. The maximum current value corresponding to 16.3 mm diameter and current rating (summer, no wind) is 216A by searching the TABLE II and TABLE III that can be passed by the wire. It is concluded that this kind of wire needs at least two same wires in parallel to make the maximum current reach 432A and then the resistance value R_1 after two parallel wires can be calculated:

$$R_1 = 0.0915\Omega/\text{km}$$

In extreme case, the utilization rate of conductor is 92.9%.

TABLE III CONDUCTOR DIAMETERS, CURRENT RATINGS AND COSTS

Conductor type/diameter	Current rating	Current rating (winter, wind<2ms^{-1})	Conductor cost
AAC 9.0 mm diameter	110A	308A	\$4,300 per km
AAC 16.3 mm diameter	216A	636A	\$6,700 per km
AAC 21.0 mm diameter	299A	875A	\$9,000 per km
AAC 26.3 mm diameter	405A	997A	\$12,300 per km
AAC 31.5 mm diameter	495A	1224A	\$16,300 per km

(3) AAC 21.0 mm diameter conductor analysis

The maximum DC resistance at 20°C of 21.0 mm diameter can be found through [3], and the resistance value R of a bundle of transmission lines is 0.11 Ω / km. The maximum current value corresponding to 21.0 mm diameter and current rating (summer, no wind) is 299A by searching the TABLE II and TABLE III that can be passed by the wire. By comparing the 401.4A current calculated by step1, it is concluded that this kind of wire needs at least two same wires in parallel, so that the maximum current reaches 598A. Finally, the resistance value R_1 of two parallel wires can be calculated:

$$R_1 = 0.055\Omega/\mathrm{km}$$

In extreme case, the utilization rate of conductor is 67.1%.

(4) AAC 26.3 mm diameter conductor analysis

The maximum DC resistance at 20°C of 26.3 mm diameter can be found through [3], and the resistance value R of a bundle of transmission lines is 0.0706 Ω / km. The maximum current value corresponding to 26.3 mm diameter and current rating (summer, no wind) is 405A by searching the TABLE II and TABLE III that can be passed by the wire. By comparing the 401.4A current calculated by step1, it is concluded that this kind of wire needs at least two same wires in parallel, so that the maximum current reaches 810A. Finally, the resistance value R_1 of two parallel wires can be calculated:

$$R_1 = 0.0353\Omega/\mathrm{km}$$

In extreme case, the utilization rate of conductor is 49.6%.

(5) AAC 31.5 mm diameter conductor analysis

The maximum DC resistance at 20°C of 31.5 mm diameter can be found through [3], and the resistance value R of a bundle of transmission lines is 0.0493 Ω / km. The maximum current value corresponding to 31.5 mm diameter and current rating (summer, no wind) is 495A by searching the TABLE II and TABLE III that can be passed by the wire. By comparing the 401.4A current calculated by step1, it is concluded that this kind of wire needs at least one wire in parallel, so that the maximum current reaches 495A. Finally, the resistance value R_1 of four parallel wires can be calculated:

$$R_1 = 0.0493\Omega/\mathrm{km}$$

In extreme case, the utilization rate of conductor is 81.1%.

(6) Comparison of cost per kilometer for five kinds of wires

According to the number of wires required for each of the five types of conductors, and referring to TABLE II and TABLE III available conductor diameters, current rates and costs, the cost per kilometer of each type of conductor is calculated:

AAC 9.0 mm diameter conductor analysis:

$$4{,}300 \times 4 = \$17{,}200 \text{per km}$$

AAC 16.3 mm diameter conductor analysis:

$$6{,}700 \times 2 = \$13{,}400 \text{per km}$$

AAC 21.0 mm diameter conductor analysis:

$$9{,}000 \times 2 = \$18{,}000 \text{per km}$$

AAC 26.3 mm diameter conductor analysis:

$$12{,}300 \times 2 = \$24{,}600 \text{per km}$$

AAC 31.5 mm diameter conductor analysis:

$$16{,}300 \times 1 = \$16{,}300 \text{per km}$$

(7) Determine the wire

AAC 31.5 mm diameter conductor can meet the current condition without binding. With the increase of conductor radius, the resistance will be reduced and the transmission current will be increased. In this way, the transmission line can still be used normally under the worst conditions, but the effect is not as good as "bundling". Therefore, the 31.5 mm diameter wire is excluded.

By comparing the utilization rate and cost of the other four conductors, it is found that 16.3 mm diameter conductor is the cheapest conductor, and generally the safety margin is about 90%, 9.0 mm diameter conductor is relatively expensive, 21.0 mm diameter conductor, 26.3 mm wire Diameter wires are safe to use, but there are some waste of materials and money. Therefore, 16.3 mm diameter wire was selected finally.

Step4 Analyze and determine the tower type

TABLE IV TOWER DESIGNS, SPACING AND INSTALLATION COSTS

Component	Phase Spacing	Cost
Tower type A	2.0 m	\$62,000 per km
Tower type B	2.2 m	\$74,000 per km
Tower type C	3.1 m	\$76,000 per km

(1) Referring to TABLE IV, tower type A is the cheapest.

(2) Most of the solar power plants are built in areas with more sunshine and less wind. Therefore, it is unnecessary to consider the stability of the tower, and finally choose tower type A.

Step5 Transmission line parameter calculation

Before using PowerWorld software for simulation, the equivalent impedance and equivalent admittance parameters of the new connecting wire need to be calculated.

Before calculating the equivalent impedance value Z' and the equivalent admittance value Y', calculating Z_c and γ is indispensable.

(1) The process of calculating Z'

Characteristic impedance Z_c is:

$$Z_c = \sqrt{\frac{z}{y}} \tag{1}$$

$$z = r + j\omega L \tag{2}$$

$$y = g + j\omega C \tag{3}$$

r in the formula is Resistance per unit length of wire, the inductance L is:

$$L = 0.2\log\left(\frac{\text{GMD}}{\text{GMR}}\right) \tag{4}$$

where GMR, $r'_b = (r' d_{12} d_{13} d_{14} \ldots d_{1b})^{\frac{1}{b}}$ for b conductors per bundle.

$$r' = r \cdot e^{-\frac{1}{4}} = 0.78r \tag{5}$$

Where r is the radius of the conductor. GMD (geometric mean distance) is the equivalent conductor spacing, equal to the cube root of the product of the three phase spacing.

Under normal operating conditions, the shunt conductance per unit length, which represents the leakage current over the insulators and due to corona, is negligible and g is assumed to be zero. That is, g=0.

$$C = \frac{2\pi\varepsilon_0}{ln\frac{D}{r}}\,\mu\text{F/km} \tag{6}$$

where $\varepsilon_0 = 8.85 \times 10^{-12} F/m$, D is the distance between conductors, r is the radius of the conductor

$$\gamma = \sqrt{zy} = \sqrt{(r + j\omega L)(g + j\omega C)} \tag{7}$$

Put the calculated value into the following formula:

$$Z' = Z_c\, sinh(\gamma l) \tag{8}$$

Using "(1) ~ (7)", the equivalent impedance value Z' can be calculated when the conductor type is AAC 16.3mm diameter, Tower type A, and the solar farm is connected to bus5.

$$Z' = 0.0043 + j0.015$$

(2) The process of calculating Y'

$$\frac{Y\prime}{2} = \frac{1}{Z_c} tanh(\frac{\gamma l}{2}) \tag{9}$$

l is the length of the transmission line:

$$l = 25km \tag{10}$$

In the process of solving Z', we have already obtained Z_c and γ. Using "(1), (7), (9), (10)", the equivalent impedance value Y' can be calculated when the conductor type is AAC 16.3mm diameter, Tower type A, and the solar farm is connected to bus5.

$$Y' = 0 + j0.0678$$

III. PowerWorld Simulation

When the solar farm is connected to Bus5, in the daytime, the lines in the system are not overloaded, and the voltage is also within the range of [0.95, 1.05]. Fig.6 is a simulation diagram.

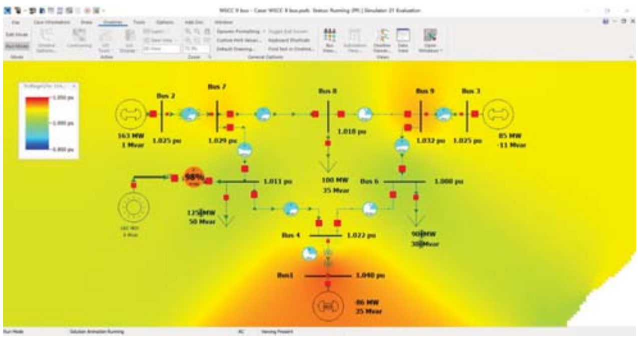

Fig.6. Power system during the day

With a 25Mvar capacitor connected in parallel on Bus5, the current on the transmission line between Bus5 and Bus10 is reduced from 98% to 96%, which reduces the risk of system overload to a certain extent, and the voltage can still meet the range of [0.95,1.05].

At night, none of the lines in the system are overloaded, and the voltages are all within the range of [0.95, 1.05]. After a 25Mvar capacitor was connected in parallel on Bus5, the current on the transmission line between Bus4 and Bus5 was reduced from 95% to 92%.

It can be concluded that, whether it is during the day or at night, the Bus5 parallel capacitor can reduce the risk of system overload to a certain extent. Fig.7 is a simulation diagram of the night system.

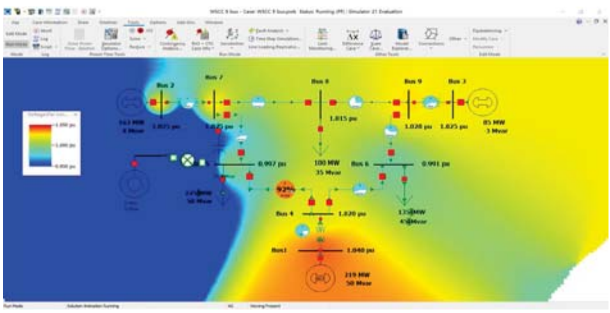

Fig.7. Power system at night

IV. Research on Power System Safety and Cost Calculation

A. Power system security solutions

Parallel transmission lines can effectively solve the overcurrent phenomenon, but at the same time it will increase the line voltage [4], [5]. After comprehensively considering the voltage and current ranges, this paper gives the following design schemes: Between Bus7 and Bus5, and between Bus5 and Bus4, add a transmission line for shunting, so that when any transmission line is disconnected, each transmission line will not overcurrent. Fig.8 is a simulation diagram of the improved system.

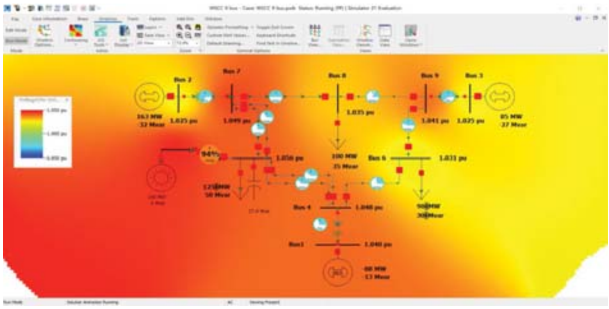

Fig.8. Improved power system

B. Cost calculation

Step1 Cost of new transmission lines

Based on the above discussion, this program chooses Bus5 as the connection bus of the solar farm, and the parameters of the transmission line are listed in the TABLE V below.

TABLE V FINAL CHOICES

	Type choose	Cost
Conductor type/diameter	AAC 16.3 mm diameter	$13400per km
Component	Tower type A	$62000per km
Conductor bundling options	Bundling spacer-2 conductors, 22cm	$35000per km

Therefore, the cost C_1 of the new transmission line satisfies:

$$C_1 = 25 \times (13400 + 62000 + 35000) = \$2{,}760{,}000$$

Step2 Cost of parallel conductors of old transmission lines

In this design, a transmission line is connected in parallel between Bus4 and Bus5 and between Bus5 and Bus7. Reference [6] can give the distance between Bus4 and Bus5 is 5290km, and the distance between Bus5 and Bus7 is 7406km.

Again, use the parameters designed for new transmission lines in this paper for calculation. Therefore, the cost C_2 of parallel conductors of old transmission lines satisfies:

$$\begin{aligned} C_2 &= (5290 + 7406) \times (13400 + 62000 + 35000) \\ &= \$1{,}401{,}638{,}400 \end{aligned}$$

Step3 Parallel capacitor and inductor cost

TABLE VI SHUNT REACTOR AND CAPACITOR COSTS

Type	Cost
Shunt capacitor	$1,000,000 per 25 Mvar
Shunt reactor	$1,000,000 per 25 Mvar

In this design, a capacitor with a capacity of 25Mvar is connected in parallel for Bus5. According to TABLE VI, the price of the parallel capacitor is $1,000,000 per 25 Mvar.

Therefore, the cost C_3 of the new transmission line satisfies:

$$C_3 = \$1{,}000{,}000$$

Step4 Total cost

The total cost C_{total} is:

$$\begin{aligned} C_{total} &= C_1 + C_2 + C_3 \\ &= \$2{,}760{,}000 + \$1{,}401{,}638{,}400 + \$1{,}000{,}000 \\ &= \$1{,}405{,}398{,}400 \end{aligned}$$

V. CONCLUSION

(1) This design connects the solar farm to Bus5, use Tower A, choose 16.33mm wire, split the two-strand connection.

(2) This paper gives the formula for calculating Z', Y'.

(3) This paper analyzes the day and night before the parallel capacitor and the day and night after the parallel capacitor through PowerWorld software.

(4) This paper analyzes the safety and stability of the power system through PowerWorld software, and gives suggestions for improvement.

(5) The total cost of this design is $1,405,398,400.

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