# MODELING AND ANALYSIS OF A THREE-PHASE POWER SYSTEM WITH RENEWABLE ENERGY INTEGRATION

EECE 450 - Final Project
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## I. INTRODUCTION

Modern power systems increasingly integrate renewable energy sources, requiring accurate modeling and power-flow analysis to ensure stable and reliable operation. This project focuses on modeling a solar-integrated three-phase power system and performing both analytical and software-based power-flow studies. The analytical portion utilizes transmission-line analysis and the Gauss–Seidel iterative method. The results are validated using ETAP simulation.

## II. OBJECTIVES

The main objectives of this project are as follows: To model a realistic three-phase power system including solar plant, transformers, transmission lines, and distribution feeders. To compute transmission-line parameters (R, L, C) from the physical line characteristics. To perform power-flow calculations using the Gauss–Seidel method. Comparing analytical results with ETAP simulation outputs. To evaluate the accuracy of the analytical model and identify sources of deviation.

## III. SYSTEM OVERVIEW

The modeled system consists of a 5-MW solar power plant interconnected through a 10-MVA step-up transformer to a 230-kV transmission network. A 130-km medium transmission line connects the high-voltage buses. A 30-MVA step-down transformer feeds a 5-km distribution feeder supplying a 3-MVA resistive three-phase load.

### A. System Design

The system is modeled as a realistic, grid- tied, balanced three phase electrical network with the integration of renewable energy. The photovoltaic power plant selected generation source connected with an inverter to supply energy to the load through transmission and distribution line and rest of the energy to the grid. The design follows the voltage stepping for efficient transmission and then down the voltage in distribution line using two transformers for a steady-state operation. Then the power is transmitted through a medium length transmission line to a receiving end substation. The structure allows the system for analysis of the voltage regulation, power-flow throughout different stages like generation, transmission, distribution and indicate the losses under operating conditions. Overall, the design follows a standard power system practice including balanced operation and symmetrical system behavior.

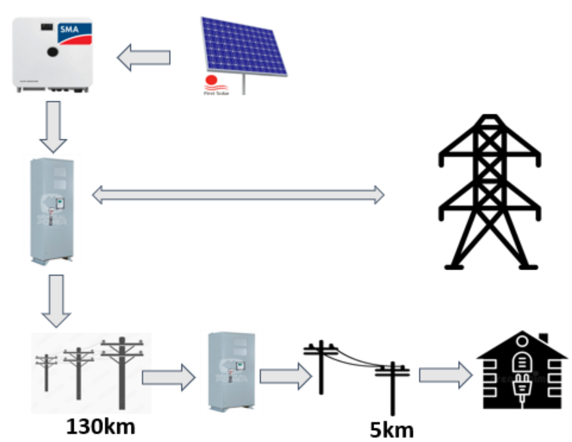


*Figure 1: Design architecture of the system*

### B. Description of Components

The complete system consists of a Solar power plant with an inverter, two transformers, transmission and distribution lines, resistive load grid tied with a substation. The source modeled as a PV plant rated as 5MW. The array producing DC power and connected with a three-phase inverter to convert the DC to AC. A three-phase 10MVA step-up transformer increases the voltage inverter's output voltage 20kV to transmission level voltage 230kV to minimize the loss. A medium length 130km long transmission line connecting the sending and receiving end with a bundle of 3 and followed nominal π- equivalent model. Other 30 MVA step-down transformers from the receiving end work to reduce the voltage from 230kv to distribution level voltage 13.8kv for a safe and efficient power supply to the load. A short distribution feeder of 5km connects the resistive load from this bus. At the end, the resistive load rated 3MVA and modeled as a completely balanced, consistent represents a practical industrial or commercial power system.

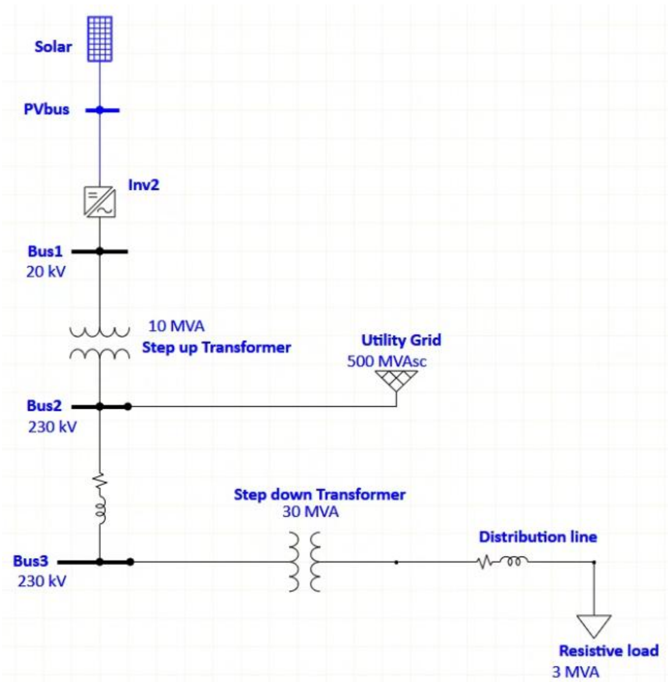


*Figure 2: Single-line Diagram of the system*

## C. Modeling in ETAP

The complete system is modeled using a power system designing a simulation tool called ETAP which is a widely used platform for integrated design and operation in all stages of a power system life cycle. A single line diagram developed integrating every single component of the system including solar, grid, transformer, lines and load. The parameter for the power plant, select First solar module in series and parallel to size it as a 5MW solar power plant generation source, 4.5 MVA inverter adjusting the voltage and current. Set the transformer a three-phase two winding configured in a Y–Δ for step up and Δ–Y connection for step down with a 30° phase shift consistent with standard practice. The transmission and distribution line length and the voltage rating as per the standardization and specified the other parameters such as resistance, impedance and capacitance to match the analytical model. The load was modeled as a balanced three-phase with its capacity selected to be compatible with the capacity of the power supply PV source and the utility grid. The finalized design is used for simulation and power flow analysis.

## D. Simulation

ETAP load flow simulation performed to evaluate the operating characteristic of the modeled power system network. The simulation conducted in the ETAP the PV and the utility grid was in service and supplying power through transmission and distribution line to load. It analyzes the active and reactive power, voltage drop, power factor, current, voltage regulation and the direction of the current. This analysis is use to compute the variable, a clear visualization of direction and the voltage profile across the generation, transmission, distribution to load.

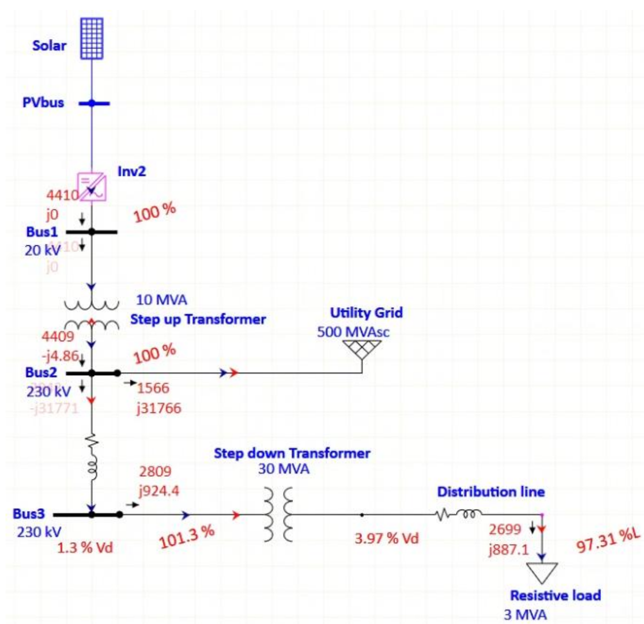


*Figure 3: Simulation result from ETAP*

## IV. CALCULATIONS

The 130-km line between Bus 2 and Bus 3 is classified as a medium-length transmission line, since its length lies between 80 km and 240 km. Medium lines must account for both series impedance and shunt capacitance, but the distributed effects are approximated using the nominal-π model, which is sufficiently accurate while keeping the analytical ABCD constants manageable.

### *A. Impedance and Admittance*

To model the line, the series impedance Z and shunt admittance Y were calculated from the line's physical parameters. The impedance calculation shown in equation 1 uses resistance and inductance values taken from the ETAP model where R=12.415 Ω and X=58.5 Ω.

$$Z = R + jX \quad (1)$$

$$R = R'\ell \quad (2)$$

$$X = X'\ell \quad (3)$$

### *B. ABCD Parameters of the Transmission Line*

The nominal-π model yields the following ABCD parameters:

$$A = D = 1 + \frac{YZ}{2} \quad (4)$$

$$B = Z \quad (5)$$

$$C = Y\left(1 + \frac{YZ}{4}\right) \quad (6)$$

Using equations 4,5 and 6 we get A = D = 0.986 + j0.0018, B = 5.96 + j45.46, and C = −5.62e−7 + j9.7e−6.

### *C. Sending and Receiving End Calculations*

First the receiving end voltage was calculated using equation 7, yielding in Vr = 132.9kV ∠0∘.

$$Vr = \frac{VrLL}{\sqrt{3}} \quad (7)$$

Next, the receiving end current was calculated using equation 8. The load specifications of the receiving end were taken from ETAP to be receiving end apparent power Sr = 3MVA and pf = 0.95. This yielded in Ir = 7.53∠-18.19∘ A.

$$Ir = \frac{S^{*}r{,}3\varphi}{3Vr} \quad (8)$$

Then the sending end voltage was calculated using equation 9. This resulted in Vs = 131, 225 ∠0.83∘ V.

$$Vs = AVr + BIr \quad (9)$$

We then found the sending end current with equation 10. This gave us Is = 7.05∠-8.15∘ A.

$$Is = CVr + DIr \quad (10)$$

Finally, we calculated the sending end apparent power using equation 11. This yielded in $Ss(3\varphi)$ = 2.78 MVA ∠8.98∘. This also resulted in a 0.99 lagging power factor.

$$Ss(3\varphi) = 3 \cdot Vs \cdot Is^{*} \quad (11)$$

### *D. Voltage Regulation*

The voltage regulation was then calculated using equation 12. Vrnl was found to be 233 kV and Vrfl was 230 kV. This resulted in the voltage regulation being 1.3%.

$VR$ % = (Vrnl – Vrfl )/ Vrfl (12)

### *E. Efficiency*

Next, the efficiency was calculated using equation 13. The receiving end power here in megawatts, Pr, is 3.83 MW and the sending end power, Ps, is 2.75 MW. This results in an efficiency of 102.9%.

$$\eta = \frac{P_R}{P_S} \times 100 \quad (13)$$

### *F. Power Loss*

The power loss was calculated using equation 14. This resulted in –0.08 MW, effectively 0 power loss.

$$P_{loss} = P_s - P_R \quad (14)$$

### *G. Gauss Seidel*

Realistically, to use Gauss Seidel analysis for the system, the calculation must take account of all four buses of the circuit. For the sake of a simpler calculation, the calculation will be calculated on bus 3 and bus 4. Assuming that at bus 4 has 20 MVA base with line impendence $Z_{line}$= 0.02+j0.06

Starting at bus 3, using the given Z calculate $Y_{line}$ at bus 3. With $Z_{cap}$ = 0.937 MVar and the load at bus 4 at 3 MVA, $Y_{cap}$ can be calculated.

$$Y_{line} = \frac{1}{Z} = \frac{1}{0.02 + j0.06} = 5 - j15\,pu$$

$$Y_{cap} = j\frac{0.93}{3} = j0.3123$$

After that, the Y bus can be constructed with the data calculated.

$$Y_{11} = Y_{line} = 5 - j15$$

$$Y_{22} = Y_{line} + Y_{cap} = 5 - j15 + j0.3123$$
$$= 5 - j14.6877 Y_{12} = Y_{21} = -Y_{line}$$
$$= -5 + j15$$

$Ybus =$

[ 5 – j15 –5 + j15 ]
[ –5 + j15 5 – j14.6877 ]

After Y bus construction, the voltage at bus 4 can be calculated

$$V_1 = 230000\angle 0° = 230000$$

$$S_2^{sch} = P_2^{sch} + jQ_2^{sch} = -2699 - j887.1$$

Initial Guess

$$V_2^{(0)} = 1\angle 0° = 1 + j0$$

Iteration 1

$$V_2^{(1)} = \frac{1}{Y_{22}}\left(\frac{-S_2^{sch}}{V_2^{(0)} *} - Y_{21}V_1\right)$$

$$V_2^{(1)} = 234380.6077 + j1675.01$$

Iteration 2

$$V_2^{(2)} = \frac{1}{Y_{22}}\left(\frac{-S_2^{sch}}{V_2^{(1)} *} - Y_{21}V_1\right)V_2^{(2)}$$
$$= 234382.5416 - j1491.91$$

*H. Active and Reactive Power*

After calculating the voltage at bus 4, these data can be used to calculate the active and reactive power of bus 3. The units used in the calculations are not in pu since the voltage of $V_1$ is not in pu.

$$P_1 = 1.12524247 \times 10^{11}$$

$$Q_1 = 1.682 \times 10^{10}$$

## V. RESULTS

The ETAP simulation was performed using identical system parameters. The ETAP results closely matched the theoretical calculations for key metrics such as voltage regulation, receiving-end current, and efficiency. Table 1 compares the analytical and simulated results.

From this table we can see the voltage regulations were identical (1.3%), confirming the accuracy of the ABCD parameters and medium-line modeling. Current magnitudes were consistent with expectations based on the small 3 MVA load at 230 kV.

Differences observed in sending-end current and power are attributed to ETAP's more detailed modeling of transformer impedances and shunt capacitance, as well as the difference between nominal voltage (230 kV) and the calculated operating voltage (133 kV).

The differences observed in Gauss-Seidel analysis can be accounted for by the line impedance assumption of $Z_{line}$= 0.02+j0.06. Since there was no line impedance given in the simulation, assumptions were made to calculate the voltage of bus 4. With the new assumption, the result of the calculations is (234382.5416 - j1419.19) compared to the simulated (2698970 + j887111)

In the simulation, we were unable to get active and reactive power at bus 3 hence there was no comparison between simulation and the calculation by hand.

| Power Flow Analysis Results | | |
|---|---|---|
| | **Calculations** | **ETAP Simulation** |
| A | 0.986 + j0.0018 | — |
| B | 5.96 + j45.46 | — |
| C | -5.62e-7 + j0.097e-4 | — |
| D | 0.986 + j0.0018 | — |

| | | |
|---|---|---|
| Receiving End Voltage | 132.9 kV ∠0 | 230 kV |
| Sending End Voltage | 131 kV ∠12 | 230 kV |
| Receiving End Current | 7.53 A ∠-18.19 | 7.3 A |
| Sending End Current | 7.05 A ∠-8.15 | 11.1 A |
| Sending End Power | 2.78 MVA ∠30 | 4.4 MVA |
| Voltage Regulation | 1.3% | 1.3% |
| Efficiency | 102.9% | 100% |
| Power loss | -0.08 MW | 0.034 MW |
| Power Flow Gauss-Seidel | 234382.5416 - j1419.19 | 2698970 + j887111 |
| Sending End Power Factor | 0.99 | 0.0492 |

*Table 1: Power Flow Analysis*

## VI. CONCLUSION

Overall, this project successfully demonstrated the complete modeling and analysis of a renewable-integrated transmission system. Voltage regulation results matched exactly between theory and simulation, validating the computed ABCD parameters and line constants. Transmission-line modeling was also consistent with ETAP behavior.

Small differences between analytical and simulation results in power-flow quantities were expected. These arise primarily from differences in assumed operating voltages, ETAP's more detailed representation of transformer and line impedances, and line-charging effects included in ETAP. Overall, the analytical calculations accurately represent system behavior and were validated by the ETAP simulation.

The project successfully teaches the basics of simulation on ETAP and power systems. The simulation then can be used to verify the calculations that were made in past examples. All in all, the project gave us a clear understanding of construction and simulation of a typical power system.