

# Integration of 75MW Solar PV Plant: Transmission System Design Analysis

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**Abstract**—This report presents the design and analysis of transmission system modifications required to integrate a new 75MW solar PV plant while addressing existing system reliability concerns. The study evaluates various transmission line and transformer options to determine the most cost-effective solution that maintains system stability under both normal and N-1 contingency conditions.

## I. INTRODUCTION

The integration of renewable energy sources into existing power grids presents technical challenges. We analyze the design requirements and potential solutions for integrating a new 75 MW utility-scale solar photo-voltaic (PV) facility into an existing 37-bus power system while also solving current reliability issues.

We aim to find the most cost-effective transmission system additions required to integrate 75 MW of solar generation at the NEWSOLAR substation. That goal is subordinate to the constraints of ensuring system reliability through dual transmission paths to the facility and resolving existing system violations identified using PowerWorld's contingency analysis.

The design must satisfy the following constraints. Bus voltages must be maintained between 0.95 and 1.10 per unit, while keeping all line flows below 100% of their thermal limits. The system must maintain stability under both normal operation and N-1 contingency conditions. Additionally, redundant transmission paths to the NEWSOLAR substation are required. The system must accommodate the solar plant operating at both full capacity (75 MW) and offline conditions.

Our approach incorporates contingency analysis, evaluation of available transmission corridors and voltage levels, and assessment of various conductor types and their associated costs. We consider transformer options and substation modifications. We conduct an economic analysis incorporating both capital costs and five-year loss reduction benefits.

Initial contingency analysis reveals specific reliability concerns in the OAK69-BUCKEYE69-APPLE69 corridor, which must be addressed alongside the integration of the new solar facility. The following sections detail the technical analysis, proposed solutions, and economic justification for the recommended design.

## II. INITIAL SYSTEM ANALYSIS

### A. Base Case Evaluation

The existing 37-bus system operates with a total load of 826.3 MW and 275.5 Mvar, served by ten generators producing 837.7 MW. System losses are approximately 10.7

MW, representing 1.3% of total generation, which indicates reasonably efficient power delivery under normal conditions. The system maintains adequate reactive power compensation through nine switched shunts, collectively providing -122.5 Mvar of reactive support.

PowerWorld's case summary for the existing system is shown in Figure 1

Case Summary for Present			
Number of Devices in Case			
Buses	38	Trans. Lines (AC)	42
Generators	10	Series Capacitors	0
Loads	26	LTCs (Control Volt)	12
Switched Shunts	9	Phase Shifters	0
2 Term. DC Lines	0	Mvar Controlling	0
Multi-Term. DC	0		
Breakers	0	Fuses	0
Disconnects	0	Load Break Disc.	0
ZBRs	0	Ground Disconnects	0
Areas	1	Islands	1
Zones	1	Interfaces	0
Substations	0	Injection Groups	0
Case pathname: Chapter6_DesignCase1Start.PWB			
Case Totals (for in-service devices only)			
	MW		Mvar
Load	826.3		275.5
Generation	837.7		102.0
Shunts	0.6		-122.5
Losses	10.7		-50.8
Dist Gen	0.0		0.0
Generator Spinning Reserves			
	Positive [MW]		Negative [MW]
	422.3		764.7
Negative MW Loads and Generators			
	MW		Mvar
Load	0.0		0.0
Generation	0.0		0.0
Slack Buses:			
SLACK345 (31); in Area 1 (1)			

Fig. 1. Case summary for existing system

### B. Contingency Analysis

PowerWorld's contingency analysis examines conditions when each element of the power system is taken offline. It reveals vulnerability in the 69 kV network in three contingency violations. Specifically, loss of either the PINE138 transformer or the PINE69-APPLE69 line results in overload, with the OAK69-BUCKEYE69 line experiencing loading up to 110.8% of its thermal limit. These violations suggest that the existing infrastructure is approaching its capacity limits.

These results are summarized in Table I. A zoomed-in view of the affected areas of the power system is shown in Figure 2.

## III. DESIGN

The design solution must incorporate new transmission infrastructure to connect the 75 MW solar facility at NEWSOLAR while simultaneously addressing existing problems. There must be redundant transmission paths to NEWSOLAR for reliability, meaning at least two separate transmission lines must be constructed. These lines can be either 69 kV or 138

TABLE I  
LINE VIOLATIONS IN CONTINGENCY ANALYSIS

Contingency	Flow(A)	Limit(A)	%
PINE138-PINE69 Xfmr:			
OAK69-BUCKEYE69	760.3	686.1	110.8
BUCKEYE69-APPLE69	454.2	418.4	108.6
PINE69-APPLE69 Line:			
OAK69-BUCKEYE69	699.2	686.1	101.9

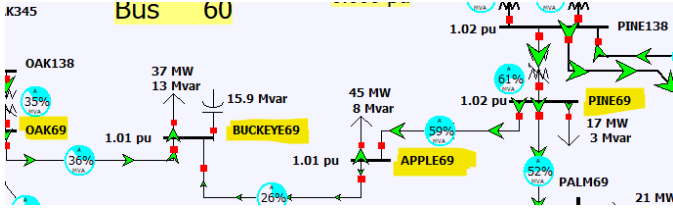


Fig. 2. Existing contingency violations - problem area

kV, with NEWSOLAR and all existing substations capable of accommodating either voltage level through installation of transformers. The system must maintain all bus voltages between 0.95 and 1.10 per unit and keep all line flows below their thermal limits under both normal operation and any single-contingency (N-1) scenario.

The optimal solution will minimize total cost, calculated as the construction costs minus any savings from reduced system losses over a 5-year period at \$60/MWh. Construction costs include both fixed components (\$1.25M for 138 kV or \$750k for 69 kV lines) and variable costs based on distance and conductor type. If 138 kV is utilized, additional costs include substation upgrades (\$900k per substation) and necessary transformers (\$1.5M for 101 MVA or \$1.8M for 168 MVA). The solution must resolve existing contingency violations, particularly the overloads observed in the OAK69-BUCKEYE69-APPLE69 corridor, while ensuring reliable operation both when the solar plant is at full output and when it is offline.

#### A. Transmission Line Parameters

A note on how to input transmission line parameters into PowerWorld is in order. Table A.4 in the text gives resistance in ohms per conductor per mile for 50°C at 60Hz as well as series inductance (ohms/mile/conductor for 1 foot spacing) and shunt capacitance (S/mile/conductor for 1 foot spacing). Resistance pulled from Table A.4 can be used directly in the "Calculate Impedances" dialog box in PowerWorld. But for 69kV lines, the three phases are spaced 2m apart and 4m apart for 138kV lines. We need a way to convert the 1-foot spacing parameters appropriately. Assuming equilateral spacing of lines, Equation 4.5.9 in the text suggests a simple way to adjust series per-mile impedance from the table:

$$X_{2m} = X_{1ft} \cdot \frac{\ln\left(\frac{2 \times 3.28}{\text{GMR}}\right)}{\ln\left(\frac{1}{\text{GMR}}\right)} \quad (1)$$

Parameter	Rook	Crow	Condor
R (Ω/mile)	0.1688	0.1482	0.1378
X (Ω/mile)	0.6421	0.6352	0.6326
B (S/mile)	$16.15 \times 10^{-6}$	$16.30 \times 10^{-6}$	$16.44 \times 10^{-6}$

TABLE II  
TRANSMISSION LINE PARAMETERS AT 60 HZ, 2M SPACING

where GMR comes from the same table for the conductor of interest. We calculate shunt susceptance manually using values given in the table:

$$B_{2m} = \frac{2\pi\epsilon}{\ln(D/r)} \quad (2)$$

where  $r$  is the conductor's outer radius. Though these are stranded conductors, we treat them as solid since the associated error is small. Note that we multiply this value by 3 for 3 phases. Table II shows parameters for the 69kV lines which go into PowerWorld's Impedance Calculator. We do not include the 138kV lines for reasons explained in the next section.

#### B. Candidate Solutions

Table III shows all possible NEWSOLAR connections to the network, given the provided set of right-of-way paths available to us. The cost of 138kV lines and transformers suggests we can eliminate any solution involving those lines; we will connect NEWSOLAR exclusively with 69kV lines unless we are unable to solve potential contingency violations. The approach here is to start with the solution involving least total line distance (case 1). We move to solutions involving longer connections only if we run into contingency violations. Further, we use the least expensive conductors to start and upgrade only if needed.

Case number	Destination buses	Total distance
1	BK69, AP69	12
2	BK69, OAK69	19
3	BK69, OAK138	19
4	AP69, OAK69	19
5	AP69, OAK138	19
6	BK69, PINE69	20
7	BK69, PINE138	20
8	AP69, PINE69	20
9	AP69, PINE138	20
10	BK69, MP69	21
11	AP69, MP69	21
12	OAK69, PINE69	27
13	OAK69, PINE138	27
14	OAK138, PINE69	27
15	OAK138, PINE138	27
16	OAK69, MP69	28
17	OAK138, MP69	28
18	PINE69, MP69	29
19	PINE138, MP69	29

TABLE III  
POSSIBLE NEWSOLAR CONNECTIONS

First we attempted to maintain NEWSOLAR at 69kV with new connections to BUCKEYE and APPLE using Condor 900A/107.5MVA conductors. We selected those stations because of their proximity to NEWSOLAR (only 6km each).

We upgraded the OAK69-BUCKEYE69 and BUCKEYE69-APPLE69 lines to the highest-rated available 69kV conductor (Condor at 900A). However, contingency analysis revealed voltage violations at OAK138, dropping to 0.939 per unit when the OAK345-OAK138 transformer is opened. This suggests a need for stronger integration with the 138kV network.

Next we installed a 138kV bus at NEWSOLAR with a 138/69kV transformer connecting it to the 69kV bus. Since voltage dropped too low at OAK in the previous design, we connected NEWSOLAR138 to OAK138 using Cardinal 1010A/241.4MVA lines. Since 138kV lines are significantly more expensive than 69kV, we kept the 69kV connection to PINE69. We found a slight overcurrent contingency violation on the OAK69-BUCKEYE69 line when PINE-APPLE is open, so we upgraded it to the 900A Condor lines. With this new configuration there are no contingency violations.

PowerWorld’s Case Summary for this configuration shows losses of 10.6MW, a 0.1MW decrease from the base scenario. That will slightly offset upgrade costs from power saving over five years. Contingency analysis showed no violations with this configuration, so we now examine the cost of this approach. Table IV shows the breakdown of costs incurred, with a total of \$20,927,200.

Modification	Cost (\$)
<b>Replace OAK-BUCKEYE (69kV Condor)</b>	
Fixed Cost	750,000
Variable Cost (\$410,000/km for 8 km)	3,280,000
<b>Total</b>	<b>4,030,000</b>
<b>138-kV Bus/101MVA Transformer</b>	
Bus	900,000
Transformer	1,500,000
<b>Total</b>	<b>2,400,000</b>
<b>New Line NEWSOLAR-OAK138 (138kV Cardinal)</b>	
Fixed Cost	1,250,000
Variable Cost (\$540,000/km for 13 km)	7,020,000
<b>Total</b>	<b>8,270,000</b>
<b>New Line NEWSOLAR-PINE69 (69kV Condor)</b>	
Fixed Cost	750,000
Variable Cost (\$410,000/km for 14 km)	5,740,000
<b>Total</b>	<b>6,490,000</b>
<b>Loss Savings (0.1 MW over 5 years)</b>	<b>-262,800</b>
<b>Grand Total</b>	<b>20,927,200</b>

TABLE IV  
COST BREAKDOWN OF TRANSMISSION LINE AND TRANSFORMER  
UPGRADES, INCLUDING LOSS SAVINGS

The massive expense of replacing lines seen in Table IV suggests that loss reduction will not pay for more line upgrades. Next we examine whether there is a better way to connect NEWSOLAR to the grid, perhaps with closer stations.

#### IV. CONCLUSION

Summary of key findings and recommendations

#### REFERENCES

- [1] PowerWorld Corporation, "PowerWorld Simulator Manual," 2024.
- [2] IEEE Standard 1547-2018, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces."