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OPENDSS FRAMEWORK FOR SYSTEM IMPACT ANALYSIS OF A 406 KW PHOTOVOLTAIC SYSTEM INTERCONNECTED TO A DISTRIBUTION FEEDER

Wei-Tzer Huang[1], Kai-Chao Yao[1], Chun-Ching Wu[1], Shyi-Wen Wang[2]
and Shin-An Yin[2]

[1]Department of Industrial Education and Technology
National Changhua University of Education
No. 2, Shi-Da Road, Changhua 50007, Taiwan
{ vichuang; kcyao; D0231007 }@cc.ncue.edu.tw

[2]Department of Electrical Engineering
Chienkuo Technology University
No. 1, Chiehshou North Road, Changhua 500, Taiwan
{ wshin; sayin }@ctu.edu.tw

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Abstract. *System impact analysis of photovoltaic (PV) systems interconnected to distribution networks is an essential task prior to the installation of these systems. Thus, the main purpose of this paper is to establish a standard system impact analysis procedure for PV systems interconnected to distribution networks. First, the PV system structure and related interconnection guides for distributed energy generation systems were discussed in detail. Second, a Taipower distribution feeder in the southern region of Taiwan was employed as the sample system, and a 406 kW PV system was interconnected to its secondary feeder. Then, the system impact analysis was accomplished using theoretical analysis, and simulation and rigorous calculation under the OpenDSS framework. Finally, the outcomes are useful for the distribution engineer and related study to realize the system impact of the PV systems interconnected to distribution networks.*

Keywords: PV system, OpenDSS, System impact analysis, Power flow, Fault current, Interconnection guide

1. **Introduction.**

The natural greenhouse effect has intensified because of human activities, primarily the burning of fossil fuels, which causes global warming, significant climate change, and more extreme weather events. According to the related assessment report from the Intergovernmental Panel on Climate Change [1,2], most of the observed increase in the global average temperature since the mid-20th century were very likely attributed to the observed increase in anthropogenic greenhouse gas concentrations [3]. Burning fossil fuel produces approximately six billion tons of CO_2 and the value is increasing annually [4]. Therefore, to reduce human emissions of greenhouse gases by minimizing energy waste and switching to low-carbon power generations of energy, such as renewable energy resources including solar, geothermal, wind power, hydro power, and tidal power, among others, is essential to mitigate global warming.

Accordingly, to promote sustainable energy development, Taiwan government has announced some major energy policies and promotion projects to encourage the use of renewable energy, such as “Thousand Wind Turbines Project” and “Million Rooftop PVs Project”. These two projects will have 3.1 GW and 4.2 GW of installed capacities, respectively, by 2030. Moreover, the total renewable energy installed capacity accounted for 16% to 20% of the total installed capacity of Taipower [4]. The government is striving to promote renewable energy. Therefore, a large number of distributed energy resources interconnected to distribution networks are expected. Consequently, some rules or guides to interconnect distributed energy resources with electric power systems are developed, such as IEEE Std. 1547 [5], California Electric Rule 21 [6], Hydro Ottawa ECG0006 [7], Technical Regulations TF 3.2.6 [8], and E.ON Netz GmbH [9]. These rules provide the interconnection standards between the power grids and distributed energy resources. According to the rules mentioned above, the system impact analysis is essential before the distributed energy resources interconnected to distribution networks; therefore, Omran et al. [10] proposed a method based on chronological simulations for PV impact evaluation, Thomson and Infield [11] performed unbalanced three-phase load-flow analysis on an entire feeder within a time-domain simulation framework for analyzing high penetration of PV, and Shirek and Lassiter [12] proposed the models of distributed energy resources for system impact study. In this paper, the system impact analysis for a 406 kW PV generation system connected to a distribution feeder of Taipower will be evaluated under OpenDSS framework following the interconnection guide for renewable energy generation system of Taipower [13]. This paper has four sections. Section 1 provides an introduction. Section 2 describes the system structure and OpenDSS. Section 3 discusses the simulation results and Section 4 concludes the paper.

2. **System Structure and OpenDSS.**

2.1. **Description of the system structure.** Figure 1 shows the single-line diagram of a practical distribution feeder that was modified from one of the distribution systems of Taipower. This system is a distribution feeder fed from a main transformer, which belongs to the 69 kV/11.4 kV secondary substation (SS). The proposed 406 kW rooftop PV system will be interconnected to a distribution feeder. According to the Taipower interconnection guides [10], the installed capacity of this PV system is below 500 kW; therefore, this system must be connected to the secondary distribution feeder whose nominal voltage is three-phase fourwire 380 V/ 220 V. The nominal voltage of the proposed system in the upstream power grid is 69 kV. The rated capacity of the main transformer is 25 MVA, and this transformer supplies five feeders, including feeder F#1. The conductor sizes of this feeder are listed in Figure 1. This system has 10 buses, and the longest distance from Bus 1 to Bus 10 is approximately 7.6 km. Bus 0 is assigned as the swing bus. Bus 2 to bus 6 are the load buses. The system already has two operating PV systems located at bus 7 and bus 8, and the total installed capacity is 140.53 kW. After the proposed 406 kW PV system is connected to bus 10, the total installed capacity is 546.53 kW, which is over 250 kW. According to the Taipower interconnection guides, the system impact analysis must be evaluated in the planning and design stages.

2.2. **Parameters for the system impact analysis.** The parameters for the system impact analysis are vital. The analysis results are more accurate when the simulation data are more detailed. In other words, the accuracy of parameters in this paper are adequate for system impact analysis in terms of the rigorous engineering analysis. The short-circuit capacity at the 69 kV side is 1140 MVA. The rating of main transformer #1 is 25 MVA, and other related parameters for simulation are listed in Table 1. The annual peak load of feeder F#1 is 4.835 MVA and 35% of the peak loading of main transforme r#1. The annual off-peak load is 2.037 MVA and 39% of the off-peak load of main transformer #1. The conductor sizes and ohms per kilometer are listed in Table 2. The proposed PV system will be connected to feeder F#1 through a 10 m long secondary distribution feeder at bus 9. The low-voltage side of a 500 kVA three-phase transformer bank with delta-grounded wye connection is connected by three 167 kVA single-phase transformers. In sum, the effects in this case is greater than that in others because the connected point belongs to the feeder end. Consequently, to evaluate the system impact analysis and to assess whether the proposed PV interconnection complies with the Taipower interconnection guides are vital.

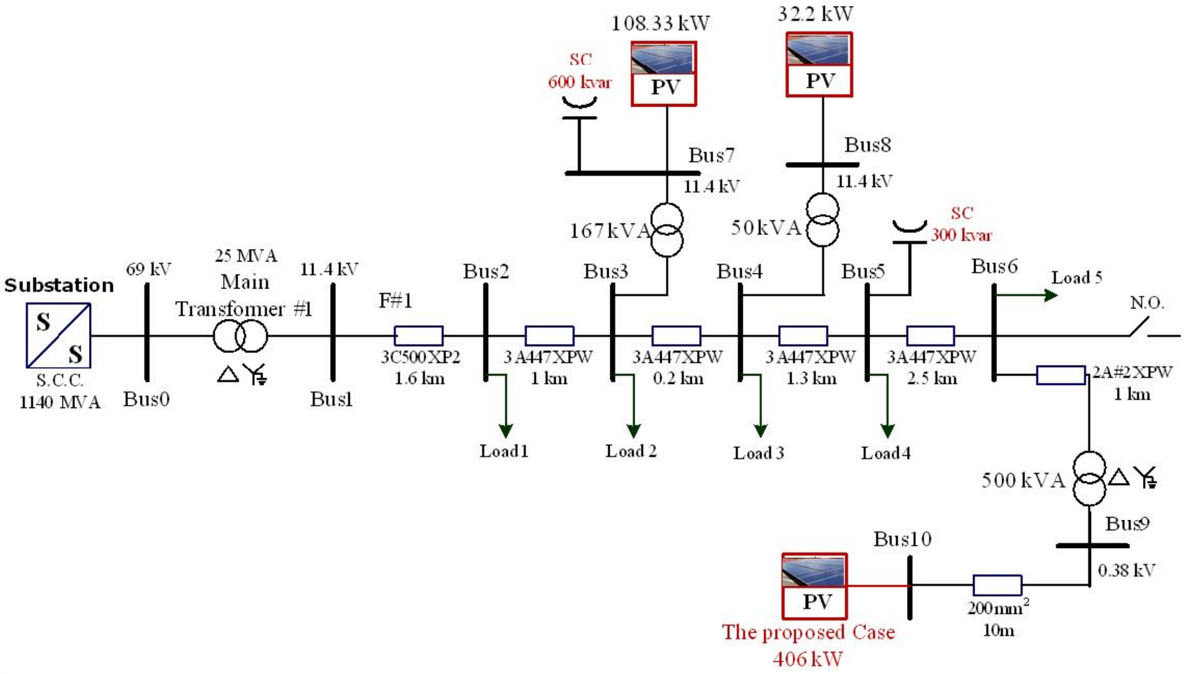

FIGURE 1. The single-line diagram of the 406 kW PV system interconnected to a distribution feeder

TABLE 1. Parameters of the main transformer

Main transformer #1				
Rating	Z%	X/R	Peak load	Off-peak load
25 MVA	8.91	25	13.735 MVA	5.2 MVA

TABLE 2. Impedances of the conductors

Conductor size	Impedance
25 kV 500 MCM	0.1075 + j0.1437 (Ω/km)
477 AAC	0.131 + j0.364 (Ω/km)
#2 AWG	0.945 + j0.506 (Ω/km)
200 mm^2	0.101 + j0.0878 (Ω/km)

2.3. **OpenDSS and simulation scenarios.** After experimenting in the mid-1990s with new approaches to study the impact of distributed generation on distribution feeders, the Distribution System Simulator (DSS) development began in 1997 at Electrotek Concepts, Inc [14]. This program has advanced over the years and obtained many new capabilities. These capabilities are quite useful for analyzing distributed generation issues [15-17]. In 2008, Electric Power Research Institute (EPRI) made the program open source to support grid modernization efforts by providing researchers and consultants with a tool to evaluate progressive ideas; therefore, the DSS was renamed OpenDSS [18]. In this paper, the OpenDSS is used to evaluate the system impact analysis including steady-state voltage variation, fault current, voltage unbalance ratio, and harmonics. The analysis and discussion issues are found in the Taipower interconnection guide. The simulation scenarios are described in Table 3. The evaluation of these scenarios are representative because the four scenarios have extreme conditions in all situations.

Table 3. Description of the simulation scenarios

Scenario	Description
Scenario #1A	Before PV system been interconnected to feeder F#1 under peak load condition
Scenario #1B	After PV system been interconnected to feeder F#1 under peak load condition
Scenario #2A	Before PV system been interconnected to feeder F#1 under off-peak load condition
Scenario #2B	After PV system been interconnected to feeder F#1 under off-peak load condition

3. Analysis and Discussion of the Simulation Results.

3.1. Steady-state voltage variation. According to the Taipower interconnection guide, the voltage variation limits at the connection point are ±2.5% for all renewable energy generation systems interconnected to the distribution system. Therefore, the formula for calculating steady-state voltage variation before and after the connection of the PV system is shown in (1).

$$VD\% = \frac{\left|V_{PV(with)}\right| - \left|V_{PV(w/o)}\right|}{\left|V_{PV(w/o)}\right|} \times 100\% \tag{1}$$

where $\left|V_{PV(with)}\right|$ is the voltage magnitude at connection point to the PV system and $\left|V_{PV(w/o)}\right|$ is the voltage magnitude at connection point to the PV system. The connection point of the low-voltage side is bus 9 and the high-voltage side is bus 6 through a distribution transformer. After running the three-power flow program by OpenDSS, the bus voltages and line flows were solved. Therefore, the voltage variation was calculated by (1), and the simulation results of steady-state voltage variation are listed in Table 4. The simulation results demonstrated that the voltage variations are below the ±2.5% limits under the annual peak and off-peak loading of the interconnected feeder. Additionally, the voltage variation at low-voltage side of the connection point is greater than that at the high-voltage side, and the maximum voltage variation at high and low voltage sides are approximately 0.72629% and 1.62043%, respectively. Moreover, the maximum reverse real power is 406.08 kW, but not beyond 30% of the rating of main transformer whose rating is 500 kVA.

Table 4. Simulation results of steady-state voltage variation at connection point

Scenario \ Connection point		Bus 6	Bus 9	Scenario \ Connection point		Bus 6	Bus 9
Scenario #1A	Phase A	0.98307	0.98307	Scenario #1 VD%	Phase A	**0.72629**	**1.62043**
	Phase B	0.98758	0.98758				
	Phase C	0.98972	0.98972		Phase B	**0.59337**	**1.49051**
Scenario #1B	Phase A	0.99021	0.99900				
	Phase B	0.99344	1.00230		Phase C	**0.55470**	**1.44283**
	Phase C	0.99521	1.00400				
Scenario #2A	Phase A	0.99287	0.99287	Scenario #2 VD%	Phase A	**0.70301**	**1.58430**
	Phase B	0.99551	0.99550				
	Phase C	0.99721	0.99721		Phase B	**0.57157**	**1.45655**
Scenario #2B	Phase A	0.99985	1.00860				
	Phase B	1.00120	1.01000		Phase C	**0.54051**	**1.41294**
	Phase C	1.00260	1.01130				

3.2. **Fault current.** The fault current analysis for the system impacts of PV connection is three-phase short circuit and single-line to ground short circuit faults. Table 5 shows the simulation results, indicating that the fault currents increased slightly after the PV interconnected to the feeder. Meanwhile, the short-circuit current is smaller than 10 kA, and these fault currents are not beyond the upper limit of the Taipower interconnection guide.

Table 5. Simulation results of fault current

Fault type / Fault point	Three-phase fault		Single-line to ground fault	
	Before connection	After connection	Before connection	After connection
Bus 1	8.9 kA	8.948 kA	9.4 kA	9.448 kA
Bus 2	6.7 kA	6.748 kA	6.9 kA	6.948 kA
Bus 3	4.8 kA	4.848 kA	4.5 kA	4.548 kA
Bus 4	4.4 kA	4.448 kA	4.4 kA	4.448 kA
Bus 5	3.3 kA	3.348 kA	3.4 kA	3.448 kA
Bus 6	2.2 kA	2.248 kA	2.2 kA	2.248 kA
Bus 9	1.7 kA	1.748 kA	1.7 kA	1.748 kA

3.3. **Three-phase balance.** According to the Taipower interconnection guide, the differences in the interconnected capacity of renewable energy generation system among the three phases in low-voltage system must be less than 5 kVA. Furthermore, referring to [5-9], the voltage and current imbalance ratios after distributed generation connection had exact definitions. Generally, the voltage unbalance ratio is less than 3%. In this practical case, the connected capacity in each phase is 135.36 kW, which is the average distributed capacity in three phases. Regardless of their capacity distributions, the simulation results of voltage unbalance ratio by OpenDSS are shown in Table 6. From the simulation results, the negative-phase voltage unbalance ratio is greater than that of zero-phase voltage unbalance ratio, and the maximum value of negative-phase voltage unbalance ratio is 0.2924%. The voltage unbalance ratio is not beyond the limits of the guide.

Table 6. Simulation results of voltage unbalance ratio at connection point

Scenario / Connection point		Bus 6	Bus 9
Scenario #1A	V_0/V_1	0.0000%	0.0000%
	V_2/V_1	0.3967%	0.3967%
Scenario #1B	V_0/V_1	0.0000%	0.0000%
	V_2/V_1	**0.2924%**	**0.2921%**
Scenario #2A	V_0/V_1	0.0000%	0.0000%
	V_2/V_1	0.2534%	0.2534%
Scenario #2B	V_0/V_1	0.0000%	0.0000%
	V_2/V_1	**0.1565%**	**0.1552%**

Note:

1. V_0 is the component of zero-sequence phase voltage;
V_1 is the component of positive-sequence phase voltage;
V_2 is the component of negative-sequence phase voltage.
2. V_0/V_1 is the zero-phase voltage unbalance ratio;
V_2/V_1 is the negative-phase voltage unbalance ratio.

3.4. **Power factor.** According to the Taipower interconnection guide, the operating power factor of distributed generation must hold 100%. The PV Mate 15 NE inverter adopted in this PV system can be operated at 100% power factor. Hence, the power factor is below the limits.

3.5. **DC component.** Based on the Taipower interconnection guide, the output DC component of the conditioner of PV system must be less than 0.5%. The test results of the DC current and DC component of the PV Mate 15 NE inverter are 0.1 A and less than 0.5%, respectively. Consequently, these values are below the limits.

3.6. **Harmonic limits.** According to the Taipower interconnection guide, the total harmonic distortion (THD) must be less than 5%, and each harmonic limit is listed in Table 7. The THD test result of PV Mate 15 NE inverter is approximately 3%; thus, the value is less than 5%.

Table 7. Harmonic current limits

Odd harmonics	Limit	Even harmonics	Limit
3rd ∼ 9th	$< 4\%$	2nd ∼ 10th	$< 1\%$
11st ∼ 15th	$< 2\%$	12nd ∼ 16th	$< 0.5\%$
17th ∼ 21st	$< 1.5\%$	18th ∼ 22nd	$< 0.375\%$
23rd ∼ 33rd	$< 0.6\%$	24th ∼ 34th	$< 0.15\%$
> 33rd	$< 0.3\%$	> 34th	$< 0.075\%$

3.7. **Discussions.** To sum up, the integrated evaluation results are listed in Table 8. The outcomes illustrated that all the analysis issues of the proposed PV system complied with the interconnection guides. Consequently, this system impact analysis case is qualified to the Taipower interconnection guide.

Table 8. Evaluation results of system impact analysis

Analysis issues	Analysis value	Limit	Qualify or not
Max. voltage variation	♦ At bus 6: 0.72629% ♦ At bus 9: 1.62043%	±2.5%	yes
Reverse power	$\leqq$ 406.08 kW	The upper limit of reverse power is below 30% of the rating of the main transformer.	yes
Max. fault current	7.228 kA	10 kA	yes
Three-phase balance	Max. voltage unbalance ratio at connection point (V_2/V_1): ♦ At bus 6: 0.2949% ♦ At bus 9: 2921%	The differences in interconnected capacity among three phases must be less than 5 kW.	yes
Power factor	100%	100%	yes
Max. DC component	Test results of the inverter are less than 0.5%.	0.5%	yes
Harmonic	Test results of the inverter are less than the harmonic limits.	Harmonic current limits are listed in Table 7.	yes

4. **Conclusions.** In this paper, the impact analysis of a 406 kW PV system interconnected to a secondary feeder was evaluated via OpenDSS. Based on the simulation results of a practical PV interconnection with Taipower distribution feeder, the three-phase power flow, short-circuit current, and voltage unbalance ratio were assessed and discussed according to related interconnection guides. The results of this paper are also useful for the distribution engineer and related study to realize the system impact of the PV systems interconnected to distribution networks.

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