# Comparative Analysis of Time-Series Studies and Transient Simulations for Impact Assessment of PV Integration on Reduced IEEE 8500 Node Feeder

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***Abstract*— This paper outlines a series of transient and time-series studies performed on a reduced version of the IEEE 8500 node feeder – as the benchmark - to compare simulation results between a transient analysis software tool such as PSCAD/EMTDC and a steady-state/time-series analysis software such as OpenDSS. The study objectives are targeted toward evaluating software tools and study approaches for investigating intermittency impact of integrating large solar photovoltaic plants into distribution systems. It should be noted that very detailed system parameters are required to develop transient models, while load flow type tools do not require such detail data. Yet, the tools need to be evaluated to ensure results are accurate enough. Operation of feeder control devices such as voltage regulators and shunt capacitors is included and compared among various scenarios. Simulations in OpenDSS are performed at different time steps to determine the ideal value based on control timing and amount of data requirements.**

## I. Introduction

Various software tools are available to perform power system analysis studies for distributed energy resource (DER) integration at distribution levels [1]. These tools usually are one of two major types: electromagnetic transient analysis software such as PSCAD/EMTDC [2], focusing on small time steps and solving differential equations for short-duration events, or steady-state analysis tools, such as OpenDSS [3], based on load flow solutions. The latter are generally much faster and can handle much larger systems, but usually have to perform a series of discrete load flow studies to capture time-varying phenomena such as impact of variations in load and generation intermittency on the operation of feeder control devices.

Time-series analysis and/or quasi-static load flow studies are normally required to evaluate impact of distributed and large-scale renewable energy resources (PV or wind) on distribution systems [4]. The studies have to be performed over several time periods to allow investigation of potential impact on time-dependent feeder control devices due to intermittency in generation and variation in feeder load for selected feeder operation conditions. Selecting a proper time step for the studies helps manage the amount of input data required for the simulations, while ensuring the accuracy in the results and outcomes.

The primary objective of this paper is to compare the simulation results and response of feeder control devices as part of a reduced version of the IEEE 8500 node feeder [5], modified to include variable loads and generators (solar PV), using both PSCAD/EMTDC and OpenDSS software packages. The aim is to test the validity of the simulation results for OpenDSS, and determine what minimum time-step can be used to obtain valid results.

## II. System Description

The system studied is derived from the IEEE 8500 node feeder; a large 12 kV benchmark feeder introduced by the IEEE distribution system modeling working group, incorporating a large number of unbalanced loads at a secondary voltage level with multiple voltage control devices [4]. Due to the impracticality of modeling all 8500 nodes in a software package such as PSCAD, the system was reduced to a more manageable 139 nodes - representing the primary backbone feeder and associated branches. The nodes associated with the secondary load connection points were combined into spot loads at the 12 kV level. The remaining nodes were selected such that all of the feeder control devices (3 voltage regulators, 4 capacitors, 3 reclosers) and main branches remained in the feeder.

Loads were grouped and represented as single phase loads with real and reactive power flows determined from the original system. They were modeled as voltage dependent loads with a dP/dV of 1 and a dQ/dV of 2. Lines were also grouped together where possible and maintain the same lengths. Control delays were represented. The load tap changer (LTC) at the source is a three phase control with an action delay of 30 seconds. The capacitor control affects all 3 phases at a time delay of 60 seconds, with a 300 seconds dead time (capacitor #3 is fixed). The voltage regulators are controlled on each phase with a delay of 45 seconds. The reduced feeder as implemented in OpenDSS as the reference benchmark is shown in Fig. 1.

Variable generators (representing solar PV plants) and loads were added to the system to analyze the feeder behavior under changing conditions. The generators were sized and positioned to reverse the power flow through regulator #3

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when fully generating (100% production). The profile used is shown in Fig. 2 as a per-unitized value.

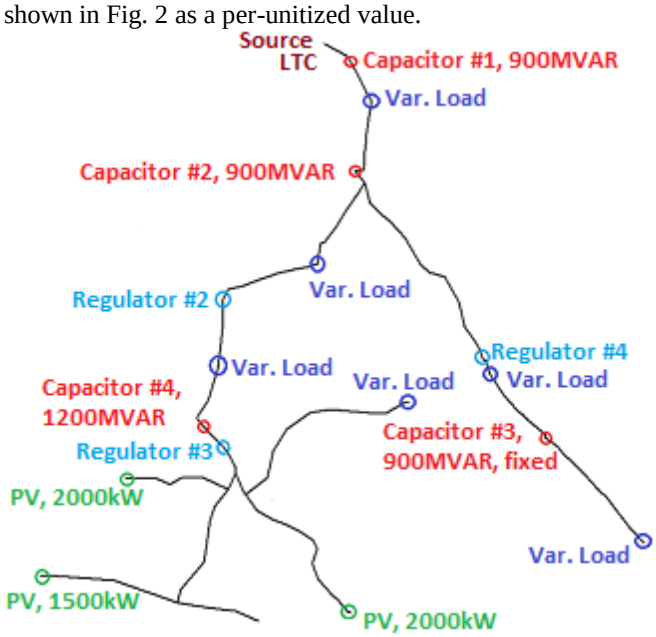


Fig. 1: Diagram of the reduced feeder system

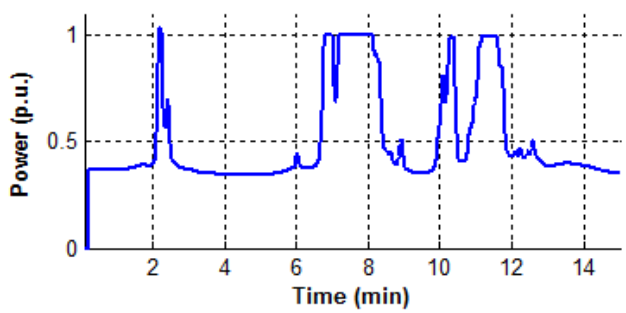


Fig. 2: PV plants generation profile

TABLE I - VARIABLE LOADS SIZES AND POSITION

| | Rated Size of the load (kVA) | | |
|---|---|---|---|
| **Variable Load Position** | **Phase a** | **Phase b** | **Phase c** |
| After Cap #1 | 121.2 | 178.0 | 134.8 |
| After Reg #4 | - | - | 371.6 |
| After Cap #3 | 139.1 | 267.0 | - |
| Before Reg #2 | 225.4 | 296.6 | 92.2 |
| After Reg #2 | 53.0 | 434.5 | 65.1 |
| After Reg #3 | 104.4 | 364.6 | 259.1 |

The variable loads replaced large loads throughout the feeder. Each load was given a different profile for both real and reactive power. As was the case for original loads, the variable loads are not balanced. Care has been used in the selection, however, to ensure all phases where included. The selected loads information is shown in Table I. Actual 1-second resolution field data over 15-minute duration was used as the generation profile for all 3 generators and all variable loads.

The simulation time intervals considered for OpenDSS were 5, 10, 15, 30, 40 and 50 seconds. The 5 sec. interval was chosen to provide a good comparison between PSCAD and OpenDSS. Below 30 seconds, the step size is small enough to allow for timely operation of the control devices (30 sec. for the source LTC, 45 sec. for the regulators and 60 sec. for the capacitors (30/45/60)). At 30 seconds, the control resolution of the voltage regulators effectively becomes 60 sec, as the time step is too large to actuate the controls every 45 sec. The 40 sec. sampling time modifies the control speeds of all the devices (40/80/80). At 50 sec, the time step is now larger than the control speed of the regulators, so their effective reaction time is decreased compared to 30 sec and 40 sec. (50/50/100).

Changing in the simulation time steps also affects the profiles. As the time step becomes larger, some fast changes are eliminated due to sampling. Fig. 3 shows the evolution in the PV generator profile as the sampling time changes.

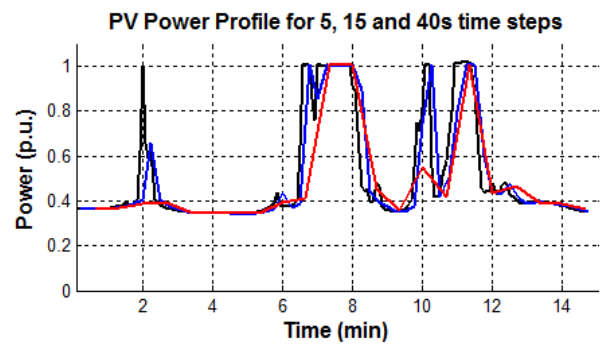


Fig 3: PV generator profile varying with sampling rate

The generation spike at t = 2 minutes starts disappearing for sampling times as short as 15 sec. One can also see noticeable smoothing of the profile. As the sampling time increases more, the spike at the 2nd minute disappears almost completely, along with the one at t = 10 minutes, the dip at t = 7 minutes also disappears. It can thus be expected that the reaction of the control devices will change as the profiles used for simulation are naturally modified with the sampling rates.

## III. STEADY-STATE SIMULATIONS

The models for PSCAD and OpenDSS were first compared under steady-state conditions to ensure their equivalency. A third party commercial software, commonly used among distribution utilities in North America, was also used to verify the implementation of the system. The voltage and power transfer through the system, as well as the steady-state position of the tap changers and the operation of the capacitors were used to compare the models. As verifications were performed for steady-state (base case) conditions, the variable loads and generators have not been included.

The power transferred through the feeder (both complex and reactive) is shown in Fig. 4 and the voltages are shown in Fig. 5. Two branches of the system were considered: The first going from the source through regulator #4 and capacitor #3 to the end of the feeder and the second from the source through regulators #2, #3 and capacitor #4 to the location of the 1500kW generator.

As can be seen, the power (both complex and reactive) matches well between the 3 software tools. The differences in voltages are due in large part to the way the software tools prioritize the control sequence.

In OpenDSS and the 3rd party software, control actions sequence is based on pre-specified priority lists for automatic devices, based on acceptable voltage thresholds in load flow solution.

For PSCAD, the system has to settle from the original conditions based on the control reaction time of each device. Therefore, the action of the controls is constrained in time and the final settling points vary from the other 2 simulations. PSCAD voltages (and tap settings) are generally higher than the other 2 software packages. They fluctuate similarly between the regulators however and remain within valid ranges in all cases. As such, they can be considered to match as well. These results show that the systems simulated in the different software packages are equivalent.

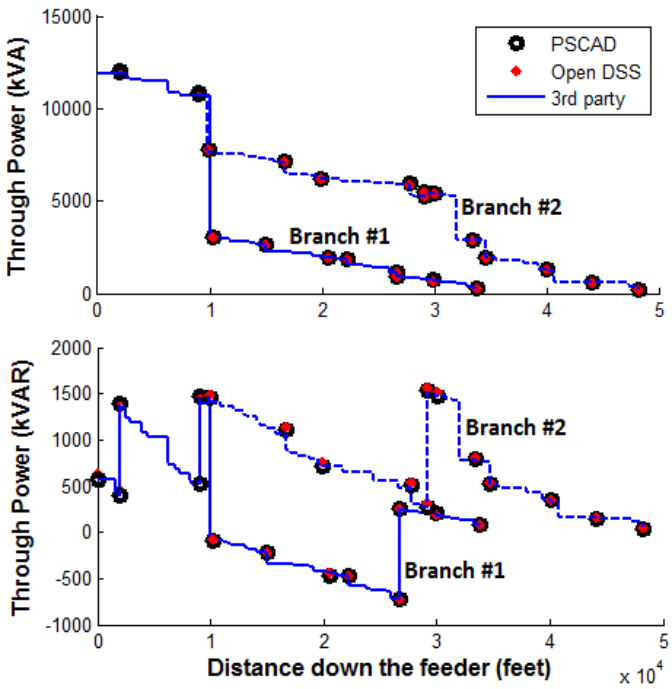


Fig. 3: Complex power (upper plot) and reactive power (lower plot) flow at different points of the feeder

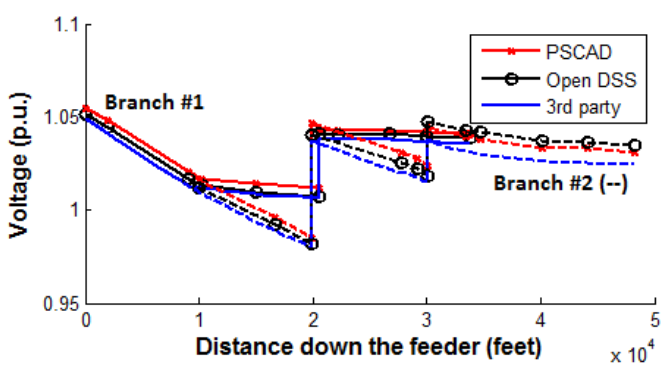


Fig. 4: Voltage at different points of the feeder

## IV. Simulation with small PV penetration

The first case considered introduces one variable PV generator, located the closest physically to regulator #3 and of total power of 2000kW, representing a relatively small penetration (16.6% of the feeder load). The results of the simulation for the tap changer, 3rd regulator and capacitor controls are shown in Table III. As it is also affected by the operation of upstream regulator #2, the voltage at regulator #3 experiences large fluctuations during the simulation, which leads to a high number of control actions. If the simulations match at that point, it can be expected that they will at other points in the feeder.

TABLE IIII
Operation of the LTC, regulator #3 and capacitors during simulation including only 1 PV generator

| | | | PSCAD | OpenDSS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5s | 10s | 15s | 30s | 40s | 50s |
| Load tap changer | | Max | 5 | 6 | 5 | 5 | 6 | 5 | 5 |
| | | Min | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| | | # of actions | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| Reg. #3 | A | Max | 7 | 6 | 6 | 6 | 6 | 6 | 7 |
| | | Min | 4 | 3 | 3 | 3 | 3 | 4 | 4 |
| | | # of actions | 7 | 6 | 7 | 5 | 8 | 2 | 7 |
| | B | Max | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | Min | 1 | 2 | 1 | 1 | 1 | 2 | 1 |
| | | # of actions | 8 | 5 | 6 | 5 | 6 | 2 | 7 |
| | C | Max | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| | | Min | -1 | -1 | -1 | -1 | -1 | 0 | 0 |
| | | # of actions | 8 | 6 | 6 | 4 | 8 | 1 | 4 |
| Cap. #1 | | Opening time (s) | 489 | 495 | - | - | 470 | - | 150 |

As the table shows, the operation of the regulators is quite similar between the software tools for a 5 sec. time step, and the capacitor operates at the same time. As the time step increases however, the capacitor does not operate as expected. It does operate around the expected time for the 30 sec. sample rate, but it did not for 10 sec or 15 sec time steps. Even without this operation, the tap range and number of changes remains relatively consistent up to a 30 sec sampling time. For the 40 sec time step, the number of actions drops, due to smoothing of the generation profile with sampling. At a 50 sec time step, the sampling time becomes longer than the regulators reaction time, causing them to operate any time the voltage fluctuates out of range for even one step, increasing the total number of actions.

The maximum voltage point of the feeder was also observed to see how the time steps affect its value. To allow for consistent comparisons, its location was determined from the PSCAD simulation. For this case, it was found to be at phase C of the PV plant, at 1.0707 per unit. The results for the simulations including the maximum change recorded for the time steps considered are shown in Table IV.

The peak value of the voltage does fluctuate between time steps, but remains in a relatively consistent range. The peak for OpenDSS is lower than in the PSCAD simulation, due to the smoothing of the generation profile. The table also shows the time of the simulation when the peak was recorded, which also varies. The peak at 11 minutes dissapears as the sampling rate decreases, at which point the longer peak around the 7th minute becomes more important. The maximum change between simulation points is much larger in OpenDSS than PSCAD as the latter uses a much smaller time step. But most importantly,

it does not fluctuate much for different time steps which leads to the possible conclusion that higher time steps do not necessarily degrade the simulation results in OpenDSS, other than by inherently smoothing fast changes in the profile.

TABLE IIIV
MAXIMUM VOLTAGE POINT DURING SIMULATION INCLUDING ONLY 1 PV PLANT

| Simulation | | Max. Voltage (p.u.) | Time of peak | Max. Change (p.u.) |
|---|---|---|---|---|
| PSCAD | | 1.0707 | 11m 12s | 0.0041 |
| OpenDSS | 5s | 1.0682 | 10m 55s | -0.0160 |
| | 10s | 1.0651 | 6m 50s | 0.0160 |
| | 15s | 1.0651 | 7m 15s | 0.0167 |
| | 30s | 1.0626 | 10m 30s | -0.0202 |
| | 40s | 1.0656 | 7m 20s | 0.0159 |
| | 50s | 1.0628 | 7m 30s | 0.0161 |

## V. SIMULATION WITH VARIABLE LOAD ONLY

The next simulation includes all variable loads but no PV plant. The smaller changes as well as their distribution throughout the feeder and through time should reduce the required control effort. The results are shown in Table V.

TABLE V
OPERATION OF THE LTC, REGULATOR #3 AND CAPACITORS DURING SIMULATION INCLUDING ONLY VARIABLE LOADS

| | | | PSCAD | OpenDSS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5s | 10s | 15s | 30s | 40s | 50s |
| Load tap changer | | Max | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | | Min | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | | # of changes | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Reg. #3 | A | Max | 7 | 6 | 6 | 6 | 6 | 6 | 6 |
| | | Min | 6 | 6 | 6 | 6 | 6 | 6 | 5 |
| | | # of changes | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| | B | Max | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | Min | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| | | # of changes | 4 | 4 | 3 | 4 | 3 | 3 | 7 |
| | C | Max | 2 | 2 | 2 | 2 | 2 | 1 | 2 |
| | | Min | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | # of changes | 1 | 3 | 3 | 3 | 3 | 2 | 3 |
| Cap. #1 | | Opening time (s) | - | - | - | - | - | - | 150 |

Here, none of the capacitors require operate, reducing the number of actions of the regulators. As the changes are relatively small and slow, the larger sampling times did not significantly degrade the results, which are the same up to a 30 sec sampling time (the actuation times do vary, but the overall control effort remains the same). Using 50 sec sampling creates the only major difference with the capacitor operation, causing additional changes on the regulator.

TABLE VI - MAXIMUM VOLTAGE POINT DURING SIMULATION INCLUDING ONLY VARIABLE LOADS

| Simulation | | Max. Voltage (p.u.) | Time of peak | Max. Change (p.u.) |
|---|---|---|---|---|
| PSCAD | | 1.0591 | 8m 58s | 0.0034 |
| OpenDSS | 5s | 1.0574 | 8m 50s | -0.0092 |
| | 10s | 1.0568 | 7m 50s | -0.0095 |
| | 15s | 1.0526 | 9m | -0.0104 |
| | 30s | 1.0541 | 6m 30s | -0.0131 |
| | 40s | 1.055 | 6m | -0.0103 |
| | 50s | 1.0598 | 10m | -0.0142 |

For this case, the maximum voltage point was found to be phase B of regulator #2; with a voltage of 1.0591 pu. The results of the simulations are shown in Table VI. Here again, the peaks in OpenDSS are lower than the PSCAD result due to smoothing, but they are generally close to the expected values. This shows that, in the absence of large or abrupt variations OpenDSS yields accurate results even at large time steps.

## VI. SIMULATION WITH LARGE PV PENETRATION AND VARIABLE LOADS

The last simulation maximizes fluctuations by including all 3 PV plants and the variable loads. This scenario is likely to produce the largest differences between PSCAD and OpenDSS, as well as between the different time steps in OpenDSS. The results are shown in Table VII. For this scenario, total simulation run times were also recorded.

TABLE VII
OPERATION OF THE LTC, REGULATOR #3 AND CAPACITORS DURING SIMULATION INCLUDING ALL PV PLANTS AND VARIABLE LOADS

| | | | PSCAD | OpenDSS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5s | 10s | 15s | 30s | 40s | 50s |
| Load tap changer | | Max | 6 | 7 | 7 | 6 | 6 | 6 | 6 |
| | | Min | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | | # of changes | 1 | 2 | 2 | 1 | 1 | 1 | 2 |
| Reg. #3 | A | Max | 8 | 7 | 7 | 6 | 6 | 7 | 6 |
| | | Min | 3 | 4 | 3 | 4 | 4 | 5 | 3 |
| | | # of changes | 14 | 12 | 10 | 8 | 7 | 4 | 11 |
| | B | Max | 5 | 4 | 4 | 5 | 4 | 4 | 5 |
| | | Min | -1 | -1 | 0 | 0 | 1 | 1 | 1 |
| | | # of changes | 15 | 9 | 10 | 11 | 6 | 4 | 10 |
| | C | Max | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| | | Min | -2 | -1 | 0 | -1 | -1 | 0 | -1 |
| | | # of changes | 14 | 11 | 7 | 7 | 7 | 3 | 9 |
| Cap. #1 | | Opening time (s) | 60.7 | 75 | 80 | 80 | 80 | 120 | 150 |
| Cap. #4 | | Opening time (s) | 487 | 75 | 80 | 80 | 80 | 120 | 150 |
| Simulation run time (s) | | | 16973 | 5 | 3 | 2.5 | 2 | 2 | 2 |

The first main difference between PSCAD and OpenDSS lies in the capacitor operation. In OpenDSS, both capacitors operate early whereas, in PSCAD, capacitor #4 does not operate until much later. In PSCAD, the first capacitor operates a fraction of a second before capacitor #4. This difference is enough to bring the voltage at capacitor #4 below the maximum and prevent its operation, which is delayed until the second generation peak. The sampling rates in OpenDSS do not allow for this type of precision.

This influences the reaction of the regulators, which affects the range and number of operations. The OpenDSS results also vary between sampling times, with the 5s sampling results being closest to the PSCAD as expected. As the sampling time increases, the peaks and dips of the profiles are smoothed out and the number of required actions is reduced. As one would expect, this more extreme case is difficult to simulate perfectly using OpenDSS. It can be noted, however, that the results are not dramatically different for the shorter time step.

The simulation times show the main advantage of OpenDSS compared to PSCAD. Although the PSCAD results are more

precise, especially during transients, the simulation was more than 3000 times longer than the longest OpenDSS time.

This simulation generated the largest maximum voltage point, which was at phase A of regulator #2, at 1.0995 pu. The results are shown in Table VIII.

TABLE VII
MAXIMUM VOLTAGE POINT DURING SIMULATION INCLUDING ALL PV PLANTS AND VARIABLE LOADS

| Simulation | | Max. Voltage (p.u.) | Time of peak | Max. Change (p.u.) |
|---|---|---|---|---|
| PSCAD | | 1.0995 | 2m 12s | -0.0069 |
| OpenDSS | 5s | 1.0975 | 6m 40s | -0.0339 |
| | 10s | 1.0973 | 6m 50s | 0.0416 |
| | 15s | 1.0910 | 6m 45s | 0.0483 |
| | 30s | 1.0911 | 7m | 0.0514 |
| | 40s | 1.0940 | 7m 20s | 0.0442 |
| | 50s | 1.0881 | 7m 30s | 0.0431 |

As Table VII shows, the peak values, although they are located around the same time, fluctuate quite a bit between the different sampling times, with the value remaining close to the PSCAD results for short sampling times, but dropping off starting with 15 sec time steps. As for the other scenarios, the maximum change between simulations does not become larger as the time step increases.

## VII. CONCLUSION

Selecting the proper time step and data sampling time are of major importance when performing time-series analysis (quasi steady-state load flow) using simulation software tools such as OpenDSS, if they are to be used to instead of transient analysis tools, such as PSCAD/EMTDC, in the study of cases involving variable generation and loads. The time gains obtained by using longer time steps in OpenDSS is not very large for this small system, has it has been simplified to be handled by PSCAD, but may become non-negligible for more complex ones. Care must be taken to ensure that fluctuations in loads or generation are not eliminated by large sampling time. However, by using a sampling time that properly preserves the fluctuations of the simulated profiles, this study has shown that OpenDSS can certainly yield good results much faster than PSCAD/EMTDC could.

As was seen in the cases involving slow or small changes (only one PV plant or variable loads), the OpenDSS simulations yield comparable results to PSCAD, particularly at sampling intervals of 15 sec or less. As the intervals increase, the results diverge, but this seems to be mainly due to the smoothing effect caused by the longer period used and less by the performance of the software. The results remain useful however; as the voltage peaks and general control reaction are still reasonable, and can at the very least help determine specific situations or time intervals where a separate, more precise simulation (either using a shorter time-step or an electromagnetic transient analysis software) may be useful.

In the worst case, with maximum PV penetration and variable loads, even considering large fluctuations in the generation profile, the OpenDSS simulations using a 5 sec time steps yielded similar results to the PSCAD simulations. When using correctly selected sampling periods, the overall results as seen in the number of tap changer operations, tap limits and maximum voltage do remain very similar.

OpenDSS also allows for far more expansive networks to be simulated and provides much shorter simulation times than PSCAD, even at a 5sec. time step. Although transient analysis tools remain essential to study short duration events such as faults and fast time-varying phenomena, in the cases studying the effects of variable generation and loads, time-series analysis using software tools such as OpenDSS can definitely be considered as a viable, time-saving option; especially in cases involving multiple simulation runs and/or very large distribution networks.

## VIII. ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy under Contract No. DOE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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## X. BIOGRAPHIES

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