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Time Series Simulation for Slow Dynamic Analysis in Distribution Systems with DERs

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SUMMARY

This paper proposes a time series simulation method for analysis of slow dynamics caused by intermittent Distributed Energy Resources (DERs) in distribution systems. Traditional single snapshot power flow simulations may not be suitable for analysis of modern distribution systems since they are not able to capture the effects of slow dynamic phenomena caused by DER intermittency. Electro-magnetic transient program (EMTP) based simulations definitely can handle non-stationary effects of DER, however, they can be very time consuming when long term simulation times are required or large scale systems are analysed. The proposed time series simulation method is based on multi-snapshot load-flow calculations and assigns a time stamp to the results obtained by each snapshot load-flow calculation. The proposed time series simulation starts when the system status changes (e.g., DG output change) and stops when the system reaches steady state. The proposed time series simulation method allows modelling the control logic of traditional distribution devices such as Load Tap Changers (LTC), voltage regulators, and capacitor banks. Furthermore and most important, the proposed method allows modelling modern and advanced control applications such as dynamic voltage support via DG units, DG voltage protection, charging and discharging of Battery Energy Storage Systems (BESS). The proposed methodology is tested on a modified IEEE 13-bus distribution feeder for two cases: 1) photovoltaic (PV) DG dynamic voltage regulation, and 2) combined operation of a PV DG plant and a BESS. The results obtained by the proposed method are compared with those obtained using an EMTP based simulation. The results of this comparison demonstrate the accuracy, high performance and efficiency of the proposed method.

KEYWORDS

Slow dynamic analysis, multi-snapshot snapshot load-flow calculation, distributed energy resources, time series simulation.

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I. INTRODUCTION

Proliferation of Distributed Energy Resources (DERs) and their integration in both distribution and transmission systems is one of most important challenges and transformations of modern electric power systems. DER proliferation is shifting the industry's focus from traditional centralized large scale power generation to distributed small scale power generation.

In order to accommodate DER into electric power systems, a considerable number of studies need to be done, such as load-flow analysis, voltage transient study, islanding study and ride-through review [1]-[2]. These studies require building computational models and conducting detailed simulations, with timelines ranging from seconds (such as islanding and grounding studies) to a year (such as yearly load profile and voltage profile analyses). The most common simulations needed for DER integration studies can be broadly categorized into two classes: 1) Electro-Magnetic Transients Program (EMTP)-based modelling and analysis [3]-[4], which are mainly for fast transient analysis such as capacitor switching, inrush current study, islanding study; and 2) Load-flow program based modelling and analysis [5]-[9] which are mainly for steady state or slow dynamic analysis such as snapshot load-flow simulation based worst scenario analysis, losses and loading analysis and LTC operation analysis.

Slow dynamic analyses have the objective of evaluating the impact of DER intermittent output (such as that from wind and photovoltaic distributed generators) on system voltage regulation and control. This is one of the most important analyses conducted as part of DER impact studies for both distribution [7]-[9] and transmission systems [10]. Voltage regulation devices used in distribution grids generally have time delay settings in the order of 30 to 90 seconds and the duration of DER's intermittency periods of interest can be longer. Therefore, slow dynamic studies often require simulations times in the order of several minutes or hours to achieve a more comprehensive evaluation of intermittency impacts than that obtained by traditional snapshot load flow analysis, which are typically based on worst case scenarios. Theoretically, EMTP based simulations can be used for this type of slow dynamic analysis. However, the computational burden of such simulations can be considerable, particularly for large and complex utility systems, and simulation times can increase significantly.

Since the objective of slow dynamic analysis is to identify potential impacts of DG intermittency on voltage related aspects (e.g., voltage fluctuations, operation of voltage control and regulation devices, etc), multi-snapshot load-flow simulation techniques (time-series based computations) are used [7]-[9]. Reference [7] provides an example of modelling network protectors and DG's voltage protection in time series analysis for meshed distribution secondary networks. Reference [8] and [9] uses time series long term simulations for a system with intermittent PV profile. Load-flow calculation software such as OpenDSS [11] and CYMDIST [12] also allow conducting long term dynamic simulations.

In this paper, a time series simulation for slow dynamic analysis in distribution systems with DER is proposed. It is based on multi-snapshot load-flow calculation which uses previous snapshot load-flow calculation results to initialize next snapshot load-flow calculations. The calculation starts when the system status changes, e.g., DER generation change or voltage regulator tap change, and stops when the system reaches steady state. The proposed time series simulation utilizes robust load-flow calculation engine, such as OpenDSS [11] and Matlab-PST [13], and models all time related protection/control (P/C) functions outside of load-flow calculations. This includes voltage regulator operation, DER dynamic voltage support, Battery Energy Storage System (BESS) charging and discharging, and DER voltage protection. Moreover, the simulation method assigns a time stamp to each snapshot load-flow calculation based on time delay information of all modelled P/C functions and DER intermittent profile. The following sections introduce the proposed simulation method and describe how to use multi-snapshot load-flow calculations to study intermittency related phenomena such as DER dynamic voltage support and BESS charging and discharge.

II. Methodology

In the proposed multi-snapshot load-flow calculation based time series simulation, it is assumed that transients caused by the operation of distribution system protection/control (P/C) devices and DER generation variations are negligible. From the second snapshot load-flow calculation, each snapshot load-flow calculation is driven by system status change (e.g., voltage regulator tap position change, DER generation change, etc), which are described in the latest updated load-flow input files. Results of each time snapshot load-flow calculation stands for the system status at that certain time with specific load-flow input files, which may not be the final state of system. Between two successive load-flow calculations, there is a time interval whose length is determined by the operation of the P/C devices and DERs generation profile in the system, where the timestamp of each single snapshot load-flow calculation result is determined and the proposed method is connected with time. Compared to the single snapshot load-flow algorithm, the proposed algorithm is multi-snapshot which describes of system different status with the time. A system with n different kinds of time related P/C functions and DG intermittent generation profile is used to illustrate how to determine time stamp of m-th snapshot load-flow calculation in Fig. 1.

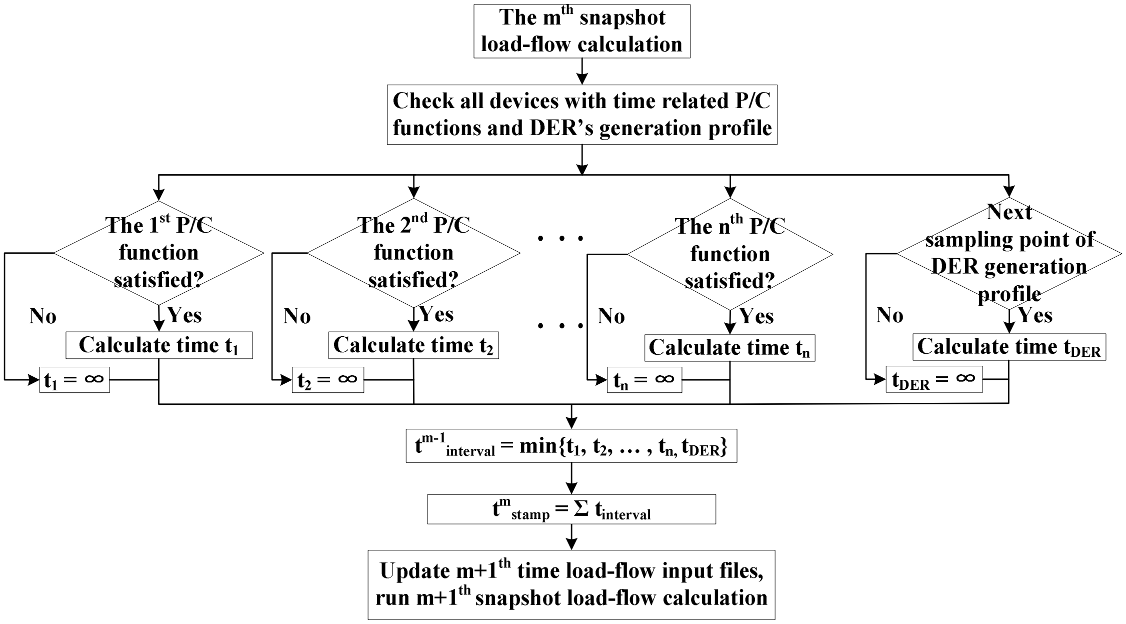

Fig. 1 Determination of time stamp for the m-th snapshot load-flow calculation

In the Fig. 1, t_n means the shortest holding time that the n-th P/C function needs in order to operation. For example, based on the m-th snapshot load-flow calculation results, the 1st P/C function (LTC changing tap) is satisfied and need hold for 45s to change the tap; the 2nd P/C function is capacitor control which is also satisfied for turning off and need hold for 60s to tripping capacitor. All other P/C function is not satisfied, and need wait for 60s for next sampling point of DER generation profile. Therefore, $t_1 = 45\text{s}$, $t_2 = 60\text{s}$, $t_n = \infty$ for all left P/C function and $t_{DER} = 60\text{s}$. Hence $t_{interval}^{m-1} = 45s$, and time stamp for m-th snapshot load-flow calculation results are the sum of time interval length from the first one to the (m-1)-th interval. Once $t_{interval}^{n} = \infty$, it means that there is no P/C function operating or new DER generation information, and the system reaches the final steady-state. The proposed multi-snapshot load-flow calculation based time series simulation will be terminated.

III Cases Study

In this section, two studied cases, as well as studied distribution model is introduced. For each of case, it is modelled in both proposed method and PSCAD. Discussion about comparison between results produced by proposed method and PSCAD are presented in detail. All simulations done via the proposed method are implemented in MS Excel VBA and use OpenDSS [11] as the load-flow calculation engine.

3.1 Modeling of studied distribution feeder

Modified IEEE 34-bus test feeder is used for study in this paper, which is shown as Fig. 2. In order to make it suitable for testing the proposed simulation method, a 500 kW PV with dynamic voltage support function is added at bus 836 for case 1 and a 50 kWh size BESS with charging and discharging power at 100 kW with PV in case 1 at bus 836 are added for case 2. Configuration of voltage regulator VR1 and VR2 are listed as following:

- VR1 – PT ratio: 120; primary CT rating: 100 A; setting voltage 122V; bandwidth: 3V; control delay: 45s; tap delay: 2s
- VR2 – PT ratio: 120; primary CT rating: 100 A; setting voltage 124V; bandwidth: 3V; control delay: 60s; tap delay: 2s

Please note that OpenDSS has the feature to model the control logic of voltage regulator. However, in order to coordinate all time related control during the simulation, voltage regulator control logic, as well as that of PV and BESS, has to be modeled outside of load-flow calculation engine as shown in Fig. 1.

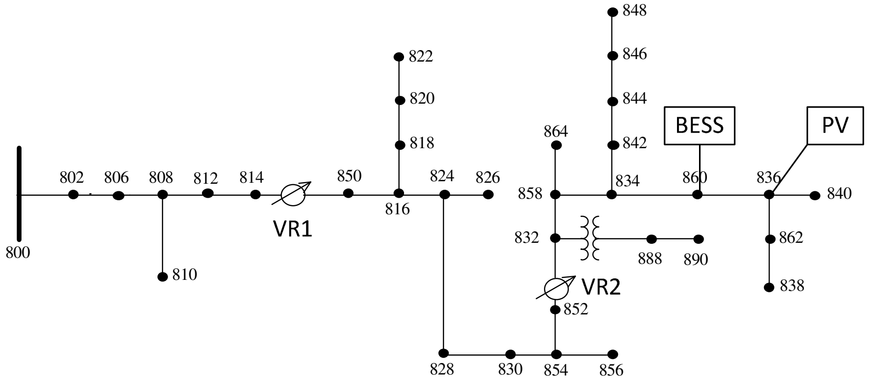

Fig. 2 Modified IEEE 34-bus test feeder for testing of proposed method

3.2 Case 1 - Simulation of PV dynamic voltage support

Assume PV connected at bus 836 as Fig. 2 is under 980s intermittency profile (1 second sampling rate) as Fig. 3 and has following dynamic voltage support feature: 1) regulating voltage of bus 836 with setting voltage is 1.04 pu and bandwidth 0.02 pu, 2) power factor range is 0.9 inductive to 0.9 capacitive, and 3) kVA rating is 550. In the PSCAD modeling, PV is model as controlled current source and in the OpenDSS, PV is modelled by "generator" element with setting active and reactive power. PV dynamic voltage support function is modelled as Fig. 4a in PSCAD and as Fig. 4b in the proposed method. It is assumed that dynamic voltage support can be finished within minimum time interval which is 1s in this case.

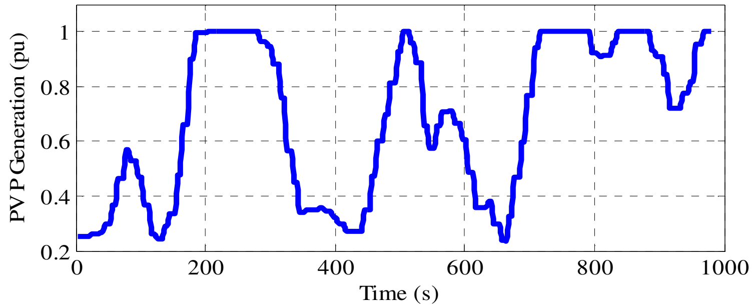

Fig. 3 PV generation intermittency profile

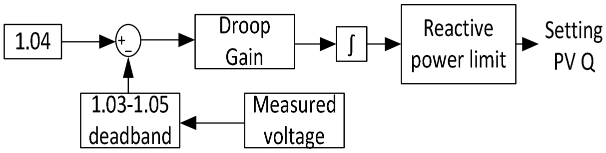

Fig. 4a PV dynamic voltage support modeling in PSCAD

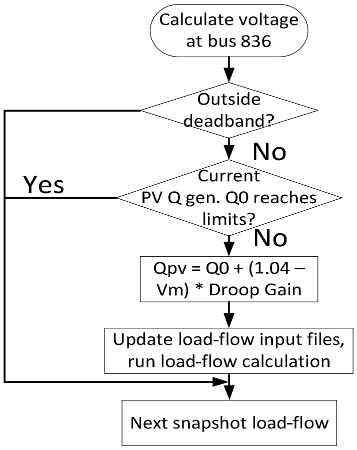

Fig. 4b PV dynamic voltage support modeling in proposed method

Based on Fig. 1 which is the main idea of proposed method, it can be found that there are 3 types of P/C logics (control of VR1, VR2 and PV voltage support) and 1 PV generation profile as Fig. 3. The proposed algorithm puts time stamp for each time of snapshot load-flow calculation based on time information of aforementioned 4 kinds of time related logics. Simulation results from proposed method and PSCAD are shown as following.

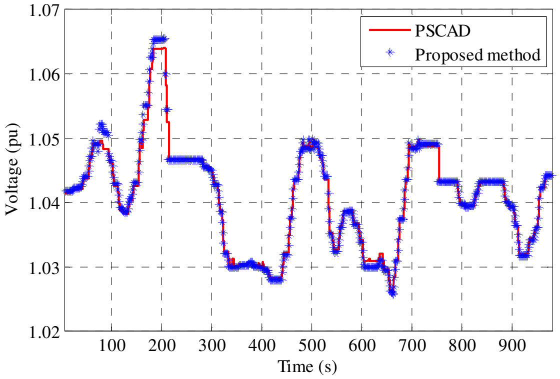

Fig. 5 Comparison of voltage at bus 836

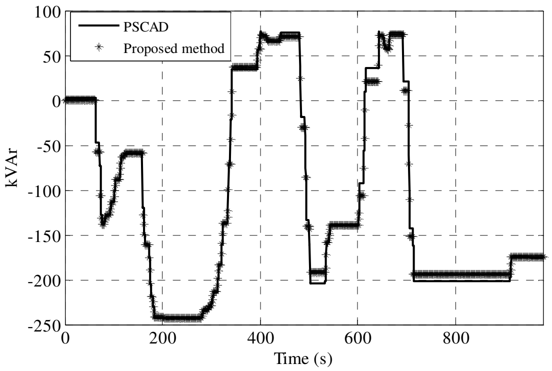

Fig. 6 Comparison of PV Q generation

Table I Comparison of voltage regulators tap position change

Voltage regulator	Tap position change		Tap changing time	
	Proposed method	PSCAD	Proposed method	PSCAD
VR1	From 1.0625 to 1.05625	From 1.0625 to 1.05625	209s	208s
	From 1. 05625to 1.05	From 1.0625 to 1.05625	211s	210s
VR2	From 1.0625 to 1.05625	From 1.0625 to 1.05625	215s	214s
	From 1. 05625to 1.05	From 1. 05625to 1.05	754s	754s

From above three kinds of comparisons which are about voltage at PV control bus, PV reactive power generation and voltage regulator tap change, it can be found that simulation results generated by proposed method are very close to those generated by PSCAD. Very small difference are shown in above comparison, which cannot be avoidable, since PSCAD simulation mechanism which is based on EMTP is completely different from proposed method which is based on load-flow calculation. Also the way to obtain RMS voltage in PSCAD simulation is different from that in the proposed method, which can cause small difference between two method, and already have been reported in previous study [7].

3.3 Case 2 - Simulation of system with PV and BESS

In this case, a 45 kWh with 100 kW rating for charging and discharging BESS is added at bus 860 as Fig. 2. It is assumed that BESS initial state of charge (SOC) is 40 kWh and voltage monitoring point is bus 860. Its control logics are described as following:

- SOC is controlled within 5% (2.25 kWh) to 95% (42.75 kWh).
- When voltage of bus 860 is higher than 1.06 pu, BESS begins to charge until SOC reaches 42.75 kWh, or voltage drop blew 1.035 pu.
- When voltage of bus 860 is lower than 1.035 pu, BESS begins to discharge until SOC drop to 2.25 kWh, or voltage rise higher than 1.062 pu.
- When voltage of bus 860 is between 1.035 pu and 1.06 pu, BESS keeps status of charging or discharging or idling.

According to the proposed method described in Fig. 1, there are four kinds of P/C control logics (control logics of VR1, VR2, PV dynamic voltage support and control logics of BESS) and 1 kind of DER generation profile (PV intermittency profile as Fig. 3) need to be modelled. In addition to compare simulation results of PV reactive power generation, voltage at bus 836, and voltage regulators tap operations, simulation results of BESS operations are also compared in this case. Comparison results are as following.

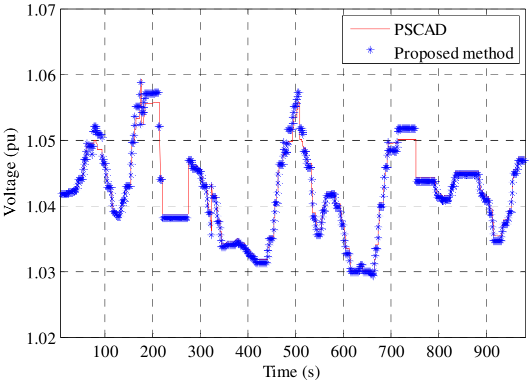

Fig. 7 Comparison of voltage at bus 836

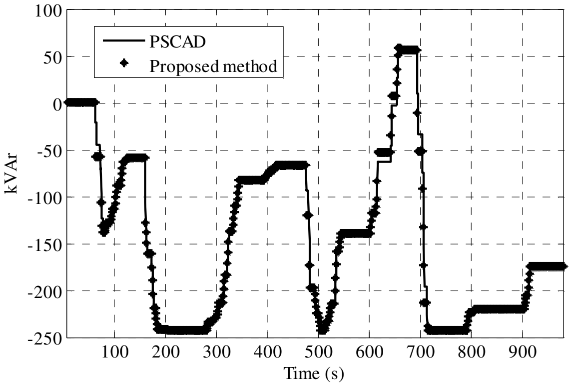

Fig. 8 Comparison of PV Q generation

Table II Comparison of voltage regulators tap position change

Voltage regulator	Tap position change		Tap changing time	
	Proposed method	PSCAD	Proposed method	PSCAD
VR1	From 1.0625 to 1.05625	From 1.0625 to 1.05625	222s	221s
	From 1. 05625to 1.05	From 1.0625 to 1.05625	510s	508s
VR2	From 1.0625 to 1.05625	From 1.0625 to 1.05625	215s	214s
	From 1. 05625to 1.05	From 1. 05625 to 1.05	217s	216s
	From 1. 05to 1.04375	From 1. 05to 1.04375	753s	752s

Table III Comparison of BESS operations

Proposed method		PSCAD	
BESS SOC (kWh)	Duration time	BESS SOC (kWh)	Duration time
40	0-174s	40	0-176s
From 40 to 42.75	174-273s	From 40 to 42.75	176-275s
42.75	273-322s	42.75	275-323s
From 42.75 to 24.5	322-980s	From 42.75 to 24.5	323-980s

From above comparisons results, it can be found that dynamic behaviour of PV and BESS simulated by the proposed method is very close to that simulated by PSCAD. Still there is unavoidable mismatch between results produced by two simulation methods, which can be negligible during DER impacts study for distribution system.

It is worth noting that for the last two cases, the time consumed by PSCAD simulations (more than 30 minutes) is notably longer than the time consumed by the proposed method (less than 30 seconds).

IV Conclusions

A multi-snapshot load-flow based simulation method for slow dynamic analysis for distribution systems with DER is proposed in this paper. Even though the slow dynamic analysis discussed in this paper is essentially a sequential steady-state analysis, it cannot be efficiently and rapidly accomplished by either single snapshot load-flow analysis or EMTP based simulations. The proposed method models all P/C functions of the devices of interest and DER intermittent profile outside of load-flow calculations, and assigns a time stamp to each snapshot load-flow calculation. The time stamp is based on time delay information of the modelled P/C functions and DER intermittent profile. A comparison study between the proposed method and PSCAD simulations shows that the proposed method is capable of *efficiently, rapidly and accurately* perform long term slow dynamic analysis for distribution systems with intermittent DER.

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