



Application of Open Distribution System Simulator (OpenDSS) In Distribution Feeders With Renewable Energy

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Abstract – Integration of renewables in the distribution feeder is on the increase. The fluctuating characteristic of renewables can potentially interrupt the operation pattern of control devices and cause voltage rise beyond permissible bounds. Open Distribution System Simulator (OpenDSS) is well suitable to determine the impact of renewables on the distribution feeder and perform a distribution power flow for small to medium sized feeders. A developed MATLAB program is integrated with distribution power flow in OpenDSS by establishing a command interface between the Matlab and OpenDSS in this paper. Matlab has the advantage to conveniently solve 24-hour linear programming problem involving daily load shape curve, renewable energy and 24 hours charge/discharge schedule for energy storage. A snapshot of Matlab commands is used to register the COM server of OpenDSS and further to set the interface. An integrated framework is developed to coordinate the activities of the control devices. The framework is programmed and simulated in OpenDSS. The developed framework is implemented hierarchically and voltage violation is checked to confirm if the distribution feeder is within permissible voltage limits. The effectiveness of the proposed methods is validated under various test cases through a time sequence analysis, over 24-hourly simulation. Test results show that OpenDSS is well suitable to determine the impact of renewables on the distribution feeder and to perform distribution power flow. In addition, the use of energy storage and demand response, effectively assist to harness renewable energy, bring further improvement to overall voltage profile and accommodate higher penetration levels of renewables.

Keywords: *Comma separated value, OpenDSS, Load shape, Load tap changers, Renewable energy.*

1. Introduction

Open Distribution System Simulator (OpenDSS) support smart grids (SGs) and SG initiatives by enabling modeling and simulation of large distribution feeders (DFs) and by enabling modeling of smart controls and smart devices. The OpenDSS is developed to support most forms of power distribution planning analysis related to the integration of distribution energy resources (DERs) to DFs [1]. Through scripting and Component Objective Model (COM) interfaces, other programs can drive OpenDSS in highly customized simulations like, Matlab, Excel, Pythom, Monte Carlo analysis, etc. Users can write their own models through scripting, dynamic linking, or automation.

OpenDSS is well suitable to determine the impact of renewable energy (RE) on DF. Some of the important built-in modes of OpenDSS are snapshot power flow, daily power flow, and yearly power flow. Others are harmonics, dynamics and fault study. In addition, OpenDSS is equally designed to perform a distribution power flow for small to medium sized feeders [2]. Power flow can be executed in various solution modes such as the duty cycle mode, daily mode, and single snapshot mode. The time duration can be any time frame and usually for planning purposes, it can be 24-hour daily, monthly or yearly. The snapshot power flow mode does one power flow solution at the present load level whereas the daily power flow mode does 24-hour solution following load shape defined as “daily”. These power flow daily modes are executed in OpenDSS standalone EXE user interface and matlab interface with OpenDSS in this paper. Example of scripts in OpenDSS standalone EXE user interface is shown in Fig. 1.

The default load shape provided in the engine or a user defined load shape can be used for a daily power flow, but different load shapes are used in this paper to drive home the objective of this study. A load shape is a curve that describes how the load, photovoltaic (PV), wind and energy storage varies with time.

Load shape can be modeled in seconds because of its uncertainty but load shapes are modeled in hour in this paper except otherwise stated. Load shape is imported from a comma separated value (CSV) and directly written to the script file in the form of load multipliers. Yearly power flow simulation can as well be employed with load shape defined as “yearly” similar to the daily mode.

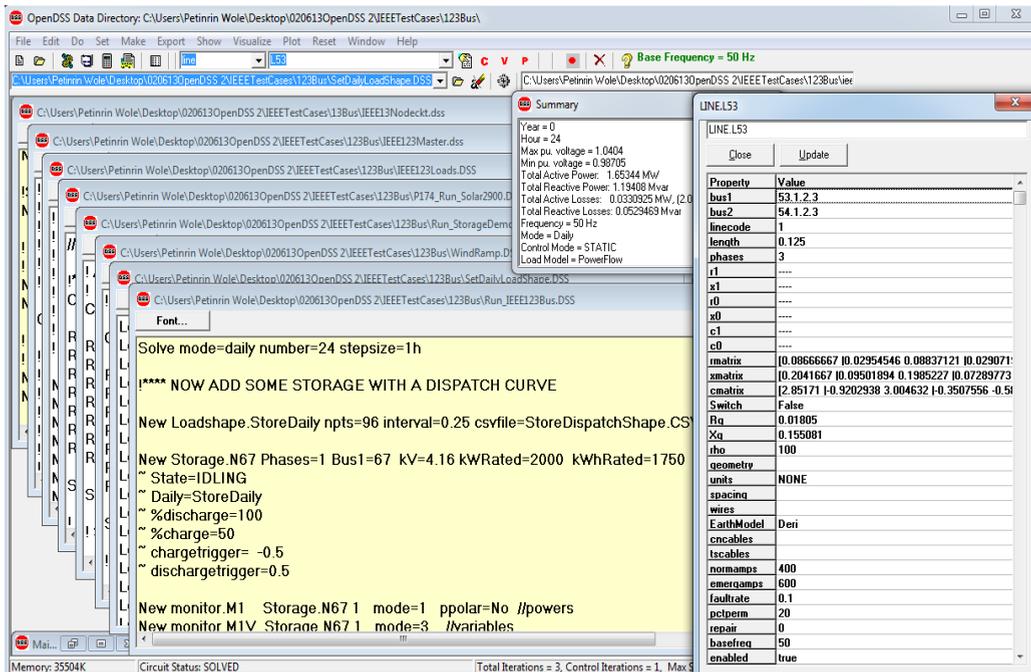


Fig. 1 OpenDSS standalone EXE user interface

The dynamic solution mode, to be preceded by a successful power flow which is suitable for simple dynamic analysis for RE integration is used in this paper. Using dynamic solution mode enables the REs in the circuit to act as voltage source behind specific reactance. Power flows are carried out for each solution mode. At the end of the power flow simulation, voltages, current, power, losses, tap operation and other information are obtained from the system, for each component and other defined areas. OpenDSS is used to perform three phase unbalanced distribution power flow for a modified IEEE123 bus Feeders in this paper.

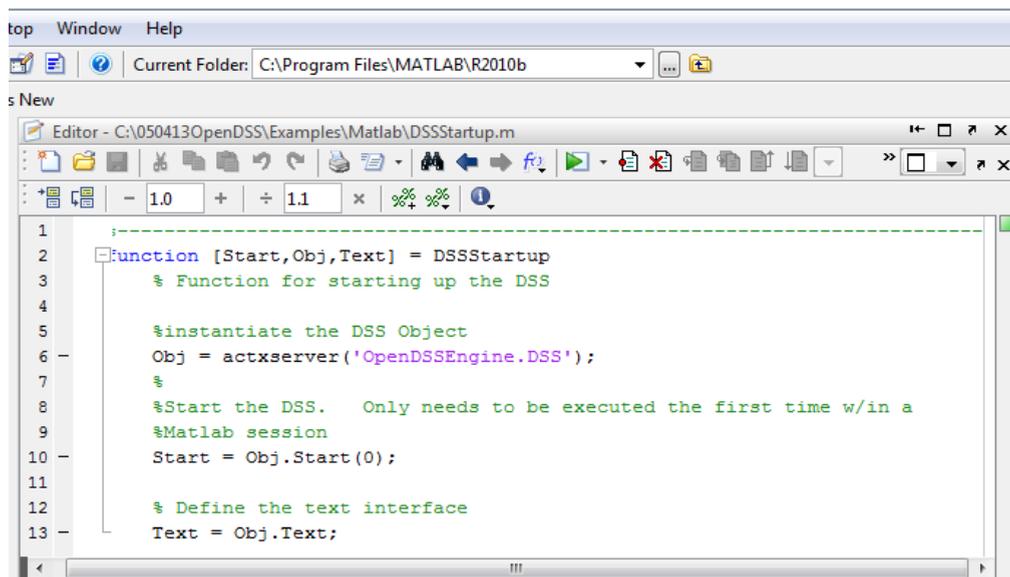
Application of voltage control techniques brings changes in control strategies which affect the number of tap operations of On-Load tap changer (OLTC), step voltage regulators (SVRs) and capacitor banks. In this paper the controls are correctly implemented in the OpenDSS with their set-points, correct delays and bands. Data to determine the operation counts of those controlled devices is provided by the OpenDSS. Typically, monitor object is used in the OpenDSS to keep track of tap positions at each solution point. The final tap positions at the end of a time series is recorded by the monitor. Event log is delved into in order to get the accurate counting of the tap operations of regulators (OLTC and SVRs). Event log is a record of all control action events, by default, which may include regulators control tap position, energy storage element actions, capacitor switching operations and so forth.

The number of tap operations can be counted directly by setting the ‘maxtapcontrol’ (maximum tap control) in the regulator control to 1. The default of this ‘maxtapcontrol’ is 16, which indicates the maximum number of tap positions that can be reached for control iteration. The regulator control (regcontrol) move the tap position of the OLTC by one tap per control iteration when the parameter “maxtapcontrol” is set to 1. Then the SVRs in the test feeder have the privilege to change their state in the next control iteration, if needed in response to this single tap position movement. The control elements

are set in the feeder using script command “RegControl.cregX.maxtapchange=1”. Where, X is regulator number in the DF. The review of the event log is carried out when the OpenDSS has completed the solution to see the actual number of tap operations. The dialog box that contains the contents of the event log up to the last solution performed can be obtained from the OpenDSS main menu.

A developed Matlab program is integrated with distribution power flow in OpenDSS by establishing a command interface between the Matlab and OpenDSS. COM interface features allow DSS to be implemented independently of any database or fixed text file definition. The use of Matlab has made it convenient to solve 24 hour linear programming problem involving daily load shape curve, renewable generations and 24 hours charge/discharge schedule for energy storage. Therefore, OpenDSS is driven from Matlab as and when required through this text interface. The main script file of OpenDSS is also edited using Matlab.

Matlab software package is used in this paper for visualization, computation of numeral and optimizations carried out in OpenDSS. Users do not require specifying the dimension of a matrix. Thus, it is easier to perform technical computation in Matlab than if one writes program in non-interactive language. There are several “Toolboxes” available for developers of Matlab. These “Toolboxes” are collection of scripts files designed for special applications, such as image processing, signal processing, and control system design, statistics and data analysis. The developed MATLAB program is integrated with distribution power flow in OpenDSS by establishing a command interface between the Matlab and OpenDSS. Matlab has the advantage to conveniently solve 24 hour linear programming problem involving daily load shape curve, RE and 24 hours charge/discharge schedule for energy storage (ES). OpenDSS receives command directly from Matlab as strings using the “text” object of the Component Objective Model (COM) interface. Therefore, OpenDSS is driven from Matlab as and when required through this text interface. The main script file of OpenDSS is also edited using Matlab.



```
1  %-----
2  function [Start,Obj,Text] = DSSStartup
3      % Function for starting up the DSS
4
5      %instantiate the DSS Object
6      Obj = actxserver('OpenDSSEngine.DSS');
7      %
8      %Start the DSS. Only needs to be executed the first time w/in a
9      %Matlab session
10     Start = Obj.Start(0);
11
12     % Define the text interface
13     Text = Obj.Text;
```

Fig. 2 Starting OpenDSS from Matlab

Text-based command interface including various methods is provided with direct access by the command interface. Users' written-programs can generate scripts to do several desired function in sequence through the command interface. COM interface features allow Distribution System Simulator (DSS) to be implemented independently of any database or fixed text file definition. It can be driven completely from a Microsoft Office (MS) VBA, or any third party analysis program like Matlab, C++, Excel, Python and

other compatible languages. COM interface is used to establish communication between Matlab and OpenDSS in this paper. A snapshot of Matlab commands is used to register the COM server of OpenDSS and further to set the interface. Fig. 2 shows the Matlab command written to register the OpenDSS Com server.

2. Renewable Energy Integration on Distribution Feeder

The integration of RE have gained substantial interest recently, due to continued advancement in RE technologies and their effectiveness as a local power source; where generation is in close proximity to loads or consumers. RE, such as solar PV and wind, imposes new challenges to the distribution feeder over centralized conventional generation due to their intrinsic variability and fluctuating characteristics [3].

With the integration of RE into the distribution system close to customers, the traditional flow of power is changed from a unidirectional to a bidirectional flow [4]. Such integration may bring about some critical operational issues in the distribution feeder as far as voltage, frequency, and reactive power are concerned. The intermittent nature of solar irradiance and wind speed lead to fluctuations in electrical variables, such as variations in bus voltages that may adversely affect the power system quality.

The main problem of high penetration of RE is voltage control/management. The voltage is required to be maintained within the acceptable boundaries to guarantee proper operation of the power system and the associated loads [3]. The intermittency and uncertainty of solar and wind energies are major complications that must be addressed in order to benefit the full potentials of these renewables. Smart grid technology such as energy storage (ES) and demand response (DR) promises a solution.

ES deployment throughout the grid from generation to end-user [4] present an opportunity to transcend the power balance paradigm by storing energy during off-peak, with less line losses, and redispatch this energy when needed [5]. Alam [6], proposed distributed ES to mitigate voltage rise problem caused by solar PV in a distribution system. In [7], a coordinated control of load tap changer (LTC) and ES for voltage rise mitigation is presented. Shi [8] improved on [6] work by developing a novel framework that continuously monitored the current and voltage at the PCC to establish a real-time Thevenin equivalent circuit of the distribution system.

DR is the consumer's reaction to effectively manage their own electricity usage in response towards changes to energy price overtime. DR facilitates the integration of RE and alleviates supply pressure on utility company [9]. Voltage analysis results by [10] shows that DR has a great potential to increase the distribution system voltage at nearly all the critical nodes. It postpones the need for network upgrades and reduces overall plant and capital cost investments [11]. The importance of VAr control devices, ES and DR in voltage control in a distribution feeder with high penetration of RE using OpenDSS is demonstrated in this paper.

3. Methodology

An integrated framework is developed to coordinate the activities of the control devices. The framework is programmed and simulated in OpenDSS [9]. It is a simulation system/tool for electric utility DF. It is used in this paper as a stand-alone executable programme and a COM interface from Matlab as shown in Fig. 3. Random variables are calculated with Matlab. Matlab is also used to control the execution of the procedure.

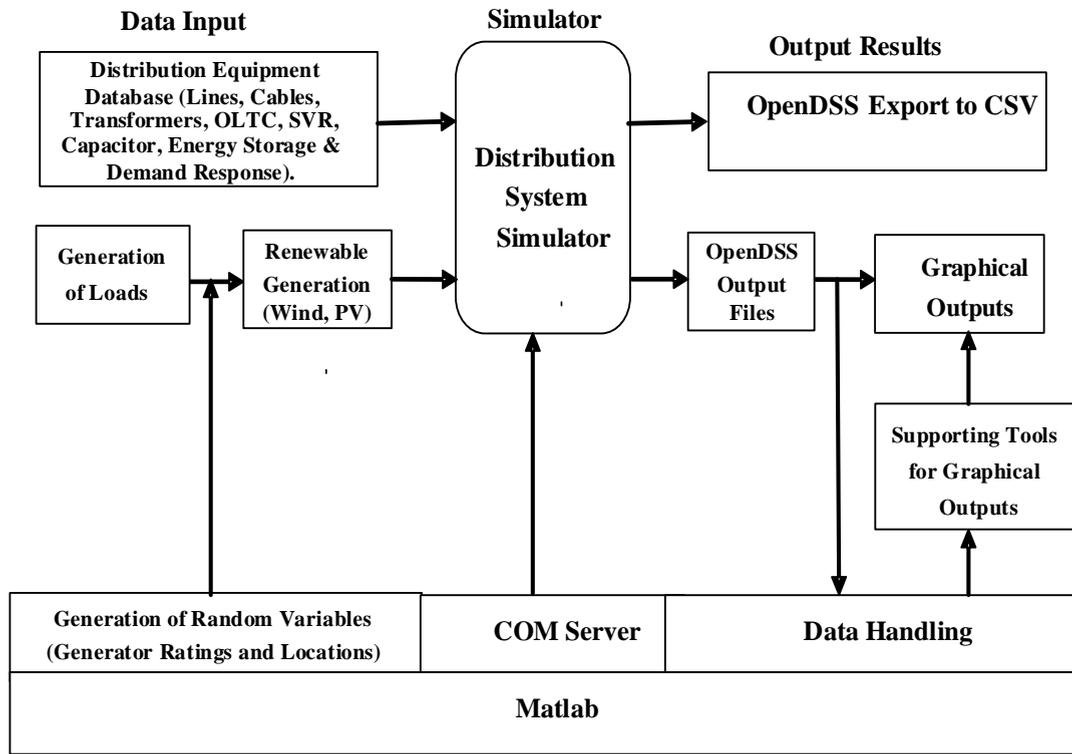


Fig. 3 Block diagram of the framework

The developed framework is implemented hierarchically and voltage violation is checked to confirm if the distribution network is within permissible voltage limits [4]. The LTC is first engaged and confirm that the permissible voltage range and LTC range are not violated or else the capacitors are enabled if either the voltage bounds or the LTC range is violated. If the LTCs and the capacitors could not regulate the voltage to permissible limits, the ES can be used to inject energy to or absorb energy from the DF depending on the voltage profile. Finally, the DR can also be applied when other control devices fall short in restoring the voltage to permissible bound. The detailed flowchart of each step in carrying out the whole simulation in this paper is shown in Fig. 4.

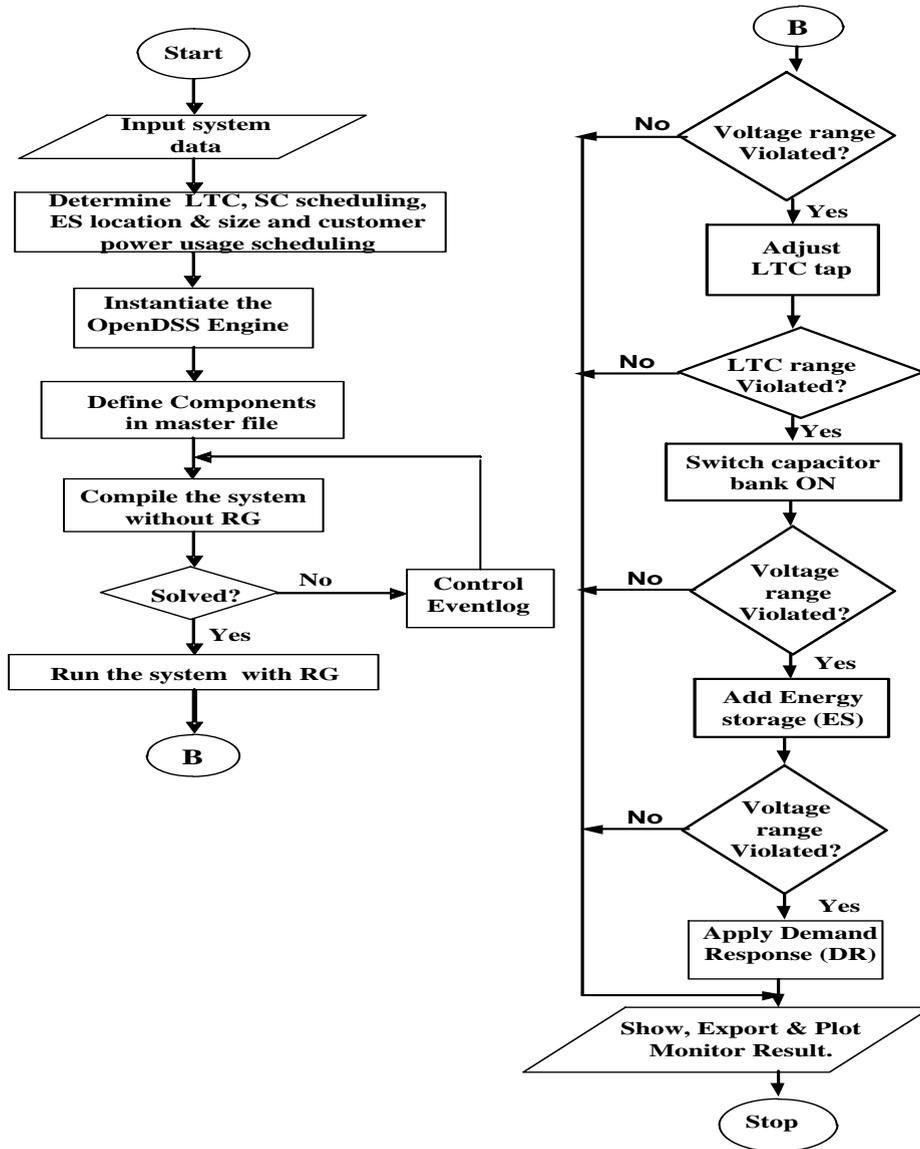


Fig. 4 Model flowchart

4. Discursion and Results

The effectiveness of the proposed methods is validated under various test cases through a time sequence analysis, over 24-hourly simulation. The adopted methods are tested on a network from a modeled IEEE 13, IEEE 123 bus feeders of an actual 5MVA 115 kV/4.16 kV 50Hz distribution feeder with different loads distributed among commercial and residential energy consumers. The feeders consist of three-phase underground or overhead primary feeders, single-phase and double-phase line sections close to the end of the feeder laterals. Different types of loads modeled in constant current, constant impedance and constant power are at the feeder buses.

The power injections of the PV and wind energy are represented by voltage-independent active injections with zero reactive power. Different penetration levels of PV and wind energy at different network locations are contemplated in order to make sure that the method is valid under wide range of operating

conditions and credible loading scenarios. The corresponding results are recorded and analysed. The generation units used in this study are both stochastic and deterministic that is, intermittent PV and wind energy. They are considered to be of unity power factor mode distributed at different locations in IEEE 13 and IEEE 123 bus feeders as shown in Fig. 5 [12] and Fig. 6 [3][13]. PV and wind energy integrated in the feeder are to inject as much power as the energy resources permit. Excess energy harvested can be stored in the ES for redispatching when needed while the DR may be applied to reduce the peak load in order to reduce the system losses and improve the voltage profile. Details of the data used in this paper are as contained in [14-15].

The conventional wisdom of selecting optimal size and location of distributed generations in the grid is annulled in this paper, since REs such as solar and wind energy largely depend on the amount of feasible energy harvested at a particular site, as dictated by the available resource [16] and subject to dominant meteorological conditions. Therefore, the solar PV and wind energy are integrated in the feeder at a location where it is assumed that PV irradiance and wind speed may be available as shown in Fig. 5 and Fig. 6.

The program files for the power flow are written in Delphi language in OpenDSS Engine main script window and run on 64 bits Window. Delphi program language is chosen because it makes COM interface implementation easier. Some of the files are developed in MATLAB program and integrated with distribution power flow in OpenDSS by establishing a command interface between the Matlab and OpenDSS. Each program file is invoked from the Compile command in the "Run_DSS" file.

The effectiveness of the OpenDSS used in this paper is verified and compared with the work carried out in [17] and IEEE [14]. The algorithm proposed and coded in Matlab in [17] is coded in OpenDSS scripting in this study. IEEE 13 and IEEE 123 bus test feeders without RE integration are used as test case. The IEEE 13 bus test feeder power flow results when compared with [17] show that the OpenDSS software used in this study is better. Although, the two results are approximately the same, but the number of the required iterations for convergence in this study is 2 as compared to 5 iterations in [17]. This indicates the effectiveness of the OpenDSS over the compared results. Also the IEEE 123 bus test feeder power flow results using OpenDSS is compared with IEEE published result. The power flow results of the IEEE 123 using OpenDSS is the same with that of published IEEE results. This proves that the results generated from the OpenDSS are reliable and effective.

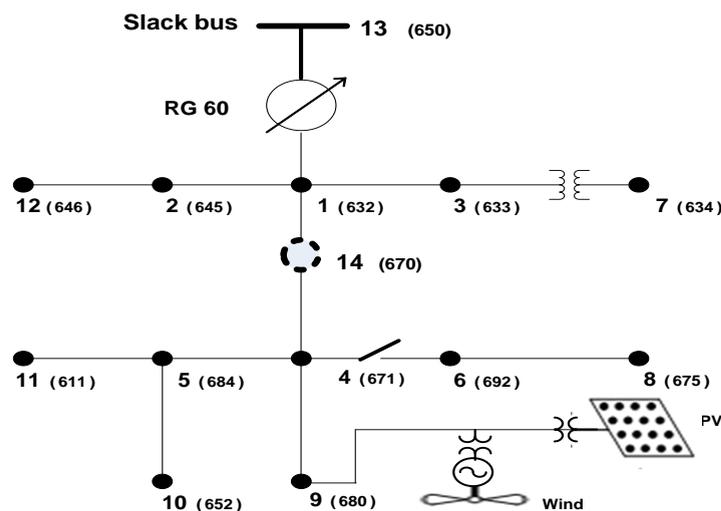


Fig. 5 Modified IEEE 13 Bus Feeders

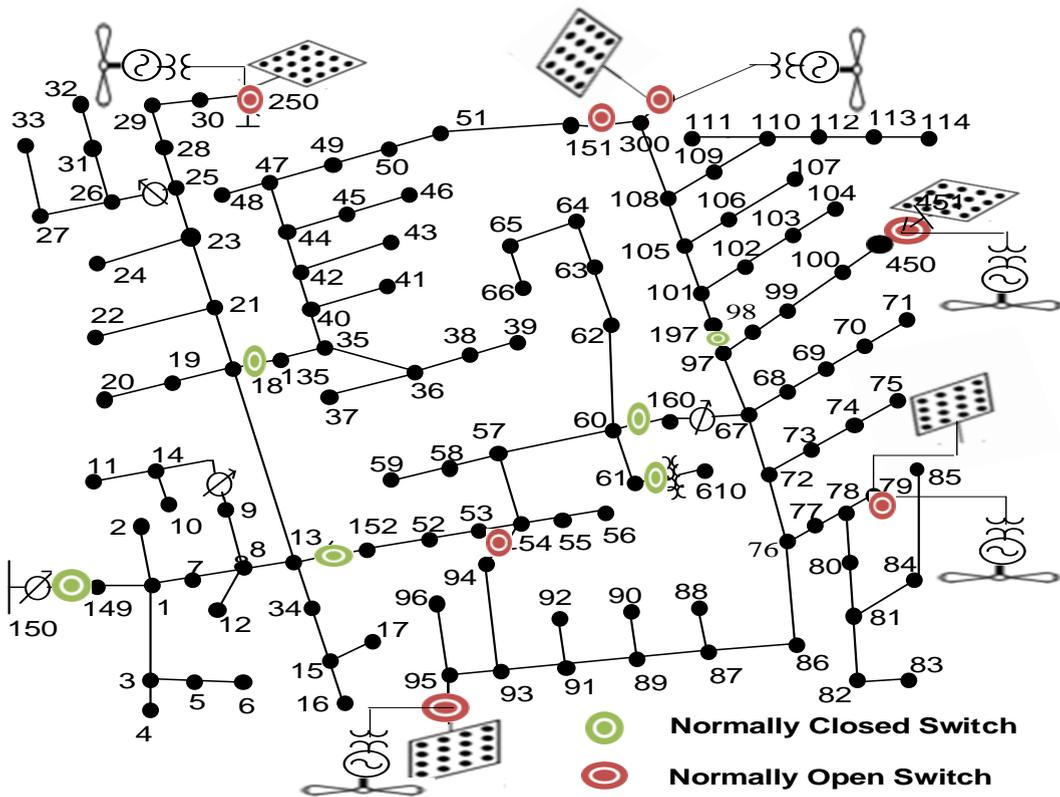


Fig. 6 Modified IEEE 123 Bus Feeders [3]

4.1. Power Flow Analysis

At a normal peak load of 3.466MW, a 30% (1.04MW) PV penetration is integrated on IEEE 13 bus feeder at bus 680 and at a normal peak load of 3.866MW, a 30% (1.16MW) PV penetration is integrated on IEEE 123 bus feeder at bus 450 and a time series 24-hour simulation is carried out on each feeder with and without PV. The results of both feeders are as shown in Table 1. The effect of PVs in multiple locations in the feeders are investigated with the PVs of the same capacity integrated in bus 633, 692 and 680 of IEEE 13 bus feeder and likewise in buses 79, 95, 250, 300 and 450 in IEEE 123 bus feeder. The results are included in Table 1.

Table 1 Voltage profile and power losses in IEEE 13 and IEEE 123 bus feeders at normal Load

	IEEE 13 Bus Feeder			IEEE 123 Bus Feeder		
	Without RE	Single RE	Multiple RE	Without RE	Single RE	Multiple RE
Tap step	1.03750	1.04375	1.04375	1.0125	1.01875	1.01875
Tap operation	2	7	7	2	3	3
Total iteration	2	3	3	2	3	3
Max pu. Voltage	1.0240	1.0302	1.0297	1.0262	1.0402	1.0378
Min pu. Voltage	1.0240	1.0244	1.0244	1.0262	1.0270	1.0267
Voltage deviation	-	0.0058	0.0053	-	0.0132	0.0111
Total active losses (MW)	0.1091 (3.05 %)	0.0895 (2.88 %)	0.0881 (2.84 %)	0.0952 (2.64 %)	0.0731 (2.36 %)	0.0736 (2.34 %)
% loss reduction	-	17%	21%	-	28%	30%

It is observed in both feeders as depicted in Table 1 that the tap operation move from 1.03750 without PV to 1.04375 with the integration of PV in IEEE 13 bus feeder while it moved from 1.0125 without PV to 1.01875 when the PV is connected in IEEE 123 bus feeder. The voltage profile increased from 1.0240 pu without PV to 1.0302 pu with PV in IEEE 13 bus feeder. In IEEE 123, the voltage profile increase from 1.0262 pu without PV to 1.0402 with PV. There is increase in tap operations as a result of voltage rise caused by the integration of the PV. However, there is reduction in system losses and better voltage profile improvement when the PV is integrated in the feeders as compared to without PV. Although the PV integrated in one location demonstrated a higher voltage profile, however, the distributed PV demonstrated lower voltage deviation and lower losses than the PV in one location. This demonstrated the potential benefits of PV distributed in DF as an alternative to conventional capacity enhancement.

4.2. Solution Mode

Solution mode which is suitable for simple analysis for the PV and wind energy integration is preceded by a successful power flow. Power flows are carried out for each solution mode and multi-period 24-hour (daily) solution mode is preferred to operate with in this paper. PV curve, wind curve, load curve saved as CSV in OpenDSS folder are called from the folder while voltage, power, losses, tap operation and other information needed are exported from the OpenDSS window to OpenDSS folder in Excel file for further analysis.

At a normal peak load of 3.866 MW, a 30% variable PV/wind energy penetration is integrated on IEEE 123 bus feeder at buses 450, 300, 250, 95 and 79 in equal proportion. A basic distribution-style power flow is carried out using OpenDSS. One power flow solution is performed by the snapshot power flow while daily/monthly/yearly (24-hour/720-hour/8760-hour) solution following load shape defined as “Daily/Monthly/Yearly” as the case may be is performed by daily/monthly/yearly power flow. A time series power flow simulation is carried out at different solution mode snapshot, daily, monthly and yearly. The PV and wind energy are examined independently.

The results of both PV and wind at different solution mode are as shown in Table 2. It is observed from the table that the snapshot mode has a low voltage profile and high losses compared with other solution modes. However, while there is higher pu voltage and lower losses during monthly solution mode for PV, it is during yearly solution mode that wind has higher pu voltage and lower losses. Also while the total iteration decreases in PV as shown in the table, the total iteration is the same for the three modes in wind energy.

Table 2 Solution mode

Solution Mode	PV				Wind			
	Snap	Daily	Monthly	Yearly	Snap	Daily	Monthly	Yearly
Total Iterations	2	7	3	2	2	3	3	3
Year	0	0	0	1	0	0	0	1
Hour	0	24	720	0	0	24	720	0
Max pu. voltage	1.0375	1.0384	1.0419	1.0379	1.0378	1.0388	1.0398	1.04
Min pu. voltage	0.9756	0.9768	0.9854	0.9788	0.9753	0.9762	0.9770	0.9771
Total Active Losses (MW)	0.1093, 2.85%	0.1044, 2.78 %	0.0745, 2.41 %	0.0955, 2.66 %	0.1093, 2.85%	0.0813, 2.46 %	0.07880, 2.43 %	0.0783, 2.42 %

4.3. Effect of Energy Storage and Demand Response on System Voltage

If the proportion of integrated RE is low there will not be a problem but when it is getting to 20%, a level proposed by European (EU) countries, then, a risk of global outage is very high [18]. Energy storage of 2.485 MW capacity is distributed with 30% wind energy in the DF so as to see the effect of ES on the system voltage. A time series 24-hour power flow simulation is carried out using OpenDSS. The VAR (OLTC, SVR and capacitors) control devices are coordinated with the ES. The dispatch action of the ES absorbs and injects more power into the feeder as the situation arises. The result is as depicted bold line in Fig. 7 with the voltage profile between 0.9752 pu and 0.9520 pu. The distribution of the ES has brought energy loss reduction, voltage profile improvement and brings the voltage within permissible bounds. Real-time pricing (RTP) DR is introduced while ES is disconnected for peak-valley levelling of the feeder. The RTP demand response is coordinated with the VAR control devices. The result is as presented dashed line in Fig. 7 with the voltage profile between 0.9771 pu and 0.9732 pu. Results unswervingly indicate that the coordinated process of the VAR control devices with ES and RTP demand response enhances system capability to maintain voltages within the statutory limits and bring reduction in system losses. The integration of ES successfully improves the voltage profile, reduced energy loss and supports to harness fluctuating RE resources. The introduction of RTP demand response underscores its significant as a solution to voltage drop problem in a DF; when the coordination of other control devices fell short in bringing back the voltage within its statutory limits. It also offers additional flexibility to the system to hedge against the variability of wind energy.

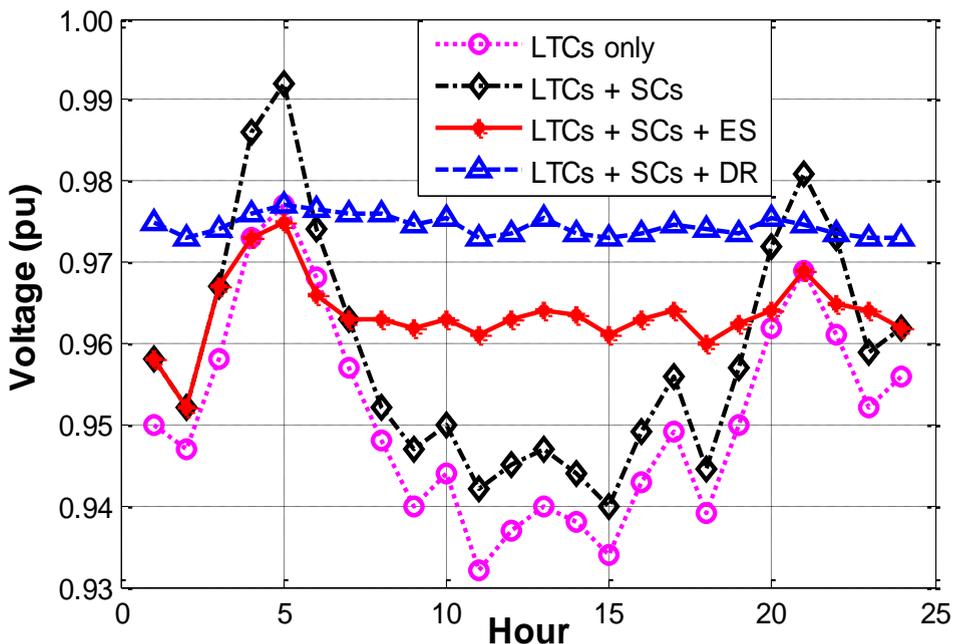


Fig. 7 Introduction of control devices at different stages

5. Conclusion

OpenDSS is developed to support most forms of power distribution planning analysis related to the integration of distribution energy resources to distribution feeders. Application of voltage control techniques brings changes in control strategies which affect the number of tap operations of On-Load tap

changer, step voltage regulators and capacitor banks. In this paper the controls are correctly implemented in the OpenDSS with their set-points, correct delays and bands. Matlab software package is used in this paper for visualization, computation of numeral and to carry out the optimizations. Users do not require specifying the dimension of a matrix. Thus, it is easier to perform technical computation in Matlab than if one writes program in non-interactive language. An integrated framework is developed to coordinate the activities of the control devices. The framework is programmed and simulated in OpenDSS.

The effectiveness of the proposed methods is validated under various test cases through a time sequence analysis, over 24-hourly simulation using Matlab Com OpenDSS. Test results show that OpenDSS is well suitable to determine the impact of PV and wind energy on the distribution feeder and to perform a distribution power flow. In addition, the voltage variation created by RE is mitigated under ES and DR concepts which provide seamless integration, reliability and optimal integration of RE and maintain the voltage profile within statutory limits.

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