IMPACT OF TRANSMISSION LINE INDUCTANCE AND CAPACITANCE ON VOLTAGE QUALITY AT PCC IN MICROGRID

[1] H. M. Karkar, [2] Dr. I. N. Trivedi, [3]R. P. Sukhadiya

[1] Ph.D. Research Scholar, [2]Associate Professor, [3] Ph.D. Research Scholar,
[1] Electrical Engineering, Gujarat Technological University, Ahmedabad, India
[2] Electrical Engineering, GEC Gandhinagar, India
[3] Electrical Engineering, Kadi Sarva Vishwavidyalaya, Gandhinagar, India

Abstract: ***In conventional grid, transmission and distribution losses is major problem today. So now a day important of microgrid is increased. Microgrid is operated in islanding and grid connected mode. In grid connected mode microgrid is connected to transmission system through Point of Common coupling (PCC). The main parameter of transmission line is inductance and capacitance. This paper presents voltage quality issues associated with inductance and capacitance, like excessive reactive power requirement for charging of transmission lines, voltage sag and increased THD in voltage at PCC when a non-linear load is connected to the system. As capacitor bank is switched on to improve the power factor. The grid tied system consists of a standalone inverter with battery. The AC output of the grid tied inverter is connected to the point of common coupling (PCC) through a power analyzer. An inductor is connected in series in the system to depict the effect of transmission line inductance present in a real power system. At PCC a capacitor bank is also connected through a multiple throw switch for power factor improvement. Voltage sag and THD analysis is find out through this hardware.***

Index Terms – Microgrid, PCC, THD, Voltage Sag

I. INTRODUCTION

This many renewable energy sources, such as wind or solar power, are uncertain by nature and thus not completely controllable. A large proportion of renewable sources comes from small-scale distributed generation and is connected to the low and medium voltage level. This is where also most loads can be found. Thus, it seems natural to attempt balancing consumption and generation locally.

The resulting local (micro) grids may be connected to the main distribution network, but can also be operated in “island mode” during faults in the main grid. This scenario implies a number of challenging control problems, which we have recently started to investigate in cooperation with Siemens AG. These include choosing suitable control architecture, handling the transition between connected and island modes and guaranteeing stability and performance in the presence of uncertainty which is inherent in renewable energy generation.

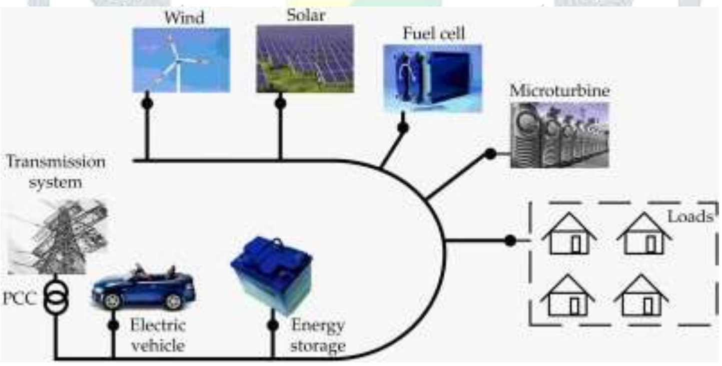

Fig. 1 Schematic representation of a microgrid with PCC referring to the point of common coupling to the main transmission system.

The Microgrid concept has been discussed as a potential means to combat problems caused by the unconventional behavior of DG and increasing DG penetration [1]. In essence a Microgrid, Fig. 1, consists of a combination of generation sources, loads and energy storage interfaced through fast acting power electronics. This combination of units is connected to the distribution network through a single Point of Common Coupling (PCC) and appears to the power network as a single unit. The aim of operating Microgrid sub-systems is to move away from considering DG as badly-behaved system components, of which a limited amount can be tolerated in an area, to good citizens. [2], i.e. an aggregate of generation and load which behave as nearly ideal conventional loads. Although the concept of using Microgrids to provide ancillary services to the local network has also been discussed, present commercial incentives are probably insufficient to encourage this.

There are two types of microgrid: AC microgrid and DC microgrid. A typical AC microgrid systems interconnected with MV system at the PCC is shown in Fig. 2. The main system could be an AC or DC bulk system. The DG units and ESS are connected at some points within the distribution networks. Part of the network consisting of the DG units and load circuits can form a small isolated AC electric power system i.e.an ‘AC microgrid’. During normal operating conditions, the two networks are interconnected at the PCC while the loads are supplied from the local sources (e.g. the RES based DG units) and if necessary from the utility. If the load demand power is less than the power produced by DG units, excess power can be exported to the main system.

In the literature, the AC microgrid systems with renewable based DG units have been researched and implemented in various countries. Their operating feasibility is discussed by a number of researchers. As per Solanki et al. [4], a smart energy management system

(SEMS) to optimize the economic operation of the micro- grid is presented. More about optimization of the DG units in microgrids can be found in [5–7].

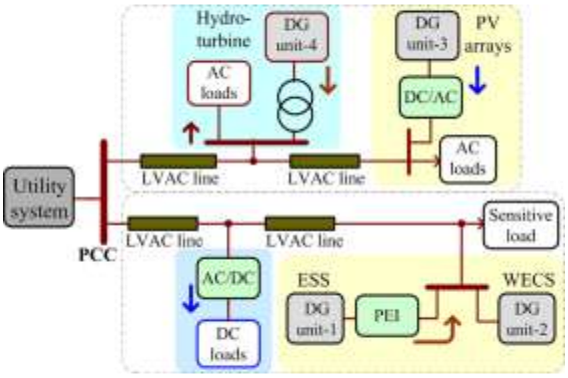

Fig. 2. AC microgrid structure with the PCC

As per Jiayi et al. [8], a review of distributed energy resources (DERs) with several technologies and MG technology are presented. The authors describe the MG operation in both grid- connected and island mode with the market environment of the MGs being also presented. Pre-planned switching and fault event leading to islanding of the distribution subsystem and formation of microgrid is presented in [9]. Guerrero et al. [10] present the hierarchical control based on the droop control methods in the AC and DC microgrids with multilevel control schemes. More emphasis in the microgrid control strategies is also given in [11,12,13].

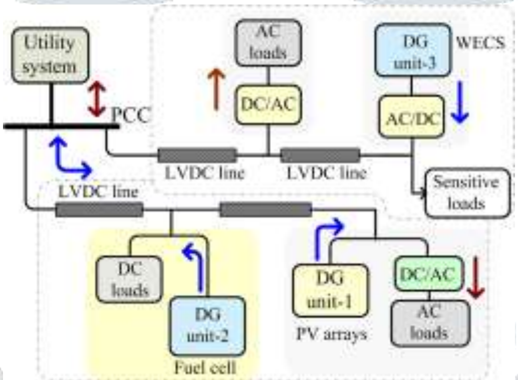

Fig. 3. DC microgrid system with the PCC

Fig. 3 shows the typical DC MG systems interconnected with the main systems at PCC which can be medium voltage AC (MVAC) network from the conventional power plants or an HVDC transmission line connecting an offshore wind farm.

The DC MG for small scale residential houses is investigated to find out the influence of current balancing, system losses together with its stability [14, 15]. The DC MG shave attractive features in terms of simple structure, low system cost and the overall improved efficiency since few power converters are needed compared to the AC MGs [16–18]. An isolated DC network which comprises solar photovoltaic(PV) systems and unbalanced AC loads was investigated. In this study, the LV DC cable to inter link the PV based DG units and their corresponding local loads [19, 20]. Also, the DC MGs control strategies in grid- connected and islanding mode are presented by several authors [21, 22].

II. TRANSMISSION LINE INDUCTANCE

Transmission lines serve as interlinks between remote power generator and distribution network. Usually transmission lines run over several of hundreds of Km and have higher X/R ratio. Also presence of power transformers in the network results in significant inductance between generator and end users or PCC. There are several power quality issues associated with inductance like excessive reactive power requirement for charging of transmission lines, voltage sag and increased THD in voltage at PCC when a non-linear load is connected to the system.

2.1 Voltage Sag

Since the transmission & distribution network has finite inductive reactance, there is always significant voltage drop when transmission lines are loaded. This voltage drop is depends on two things, inductive reactance & loading current. Again inductive reactance is function of length of transmission line. For a fixed voltage source (generator in this case), voltage varies throughout the length and different voltages appear at different nodes Secondly for the same node, voltage changes as load changes. In simple words, it is like more is the current flowing through the transmission line, more will be the drop across the transmission line reactance and more is voltage sag.

2.2 Change in THD with change transmission line inductance

Increased usages of non-linear loads like mobile/battery chargers, power electronics converters/Inverters, diode bridge rectifier is polluting the electrical network as such loads draw current with higher order harmonics present in addition to fundamental current. Such loads affect the performance of nearby load also. For example, when a high rating charger is connected at the same terminals to which an induction motor is connected, motor torque oscillation takes place which consequent as difficultly in speed control of induction motor driven conveyer belts. This phenomenon can be explained in this way. We know that 3 phase synchronous generator is most commonly used for power generation, can be considered as stiff source and generates only fundamental voltage. As discussed above significant inductive reactance (say ZTX = 2coswt) is present between generator and customer end point or say point of common coupling (PCC). Now when a nonlinear load is connected at PCC, it draws higher order harmonics current. Since generator is stiff source (say $V_S = 210 \sin \omega t$) and ideally generates fundamental voltage only, profile of voltage at PCC changes i.e. after loading with nonlinear load (let say $I_L = 10 \sin \omega t + 2 \sin 5 \omega t$

+ 0.8 sin 7ωt), higher order components appear in PCC voltage ($V_{PCC} = V_S - Z_{TX} * I_L$). For a fixed nonlinear load current, THD in voltage increases with increase in inductance.

Source Voltage, $V_S = 210 \sin \omega t$
Transmission Line Inductance, $Z_{TX} = 2 \cos \omega t$
Nonlinear Load Current, $I_L = 10 \sin \omega t + 2 \sin 5\omega t + 0.8 \sin 7\omega t$
PCC Voltage = $V_{PCC} = V_S - Z_{TX} * I_L = 210 \sin \omega t - (2 \cos \omega t) * (10 \sin \omega t + 2 \sin 5\omega t + 0.8 \sin 7\omega t)$

III. TRANSMISSION LINE CAPACITANCE

In electrical network, Power Factor is notion for actual work done calculated with respect to efforts. Basic mathematical definitions say, it is ratio of actual power and apparent power or it is cosine of angle between voltage and current in power triangle. These definitions are valid only if voltage and current quantities are sinusoidal and then power factor is expressed as dimensionless number between -1 to 1. Watt (W) is unit for active power, where as for apparent power it is Volt-Ampere (VA).

3.1 Power Factor

When the current is passing through any inductive load like arc furnace, phase of current lags the phase of source voltage; while for a capacitive load like over excited synchronous motor, phase of current leads the phase of source voltage. Since the active power calculated is given as time integral of multiplication of voltage and current averaged over a cycle, so if voltage and current are phase shifted, power calculated is less than when both are in phase. Calculated active power is keeps on decreasing as phase angle keeps on increasing and becomes zero for quad phase difference. This reflects the attribute of inductor and capacitor to act as energy source; at various points through the AC cycle the reactive power is either storing energy, or it is returning to the system.

Power supply utilities and generating bodies require their customers to present a load to the power grid that is as near to unity power factor as possible. The main, but not the only reason, is fiscal. The customer expects to pay for the “real” work done on his premises – in other words, the value of W, above. Main causes of low power factors are AC induction motors, arc lamp, electrical discharge lamp, industrial heating furnace etc.

A power factor of less than one is effectively an increase in utility’s costs, and one that they pass back to customers by imposing an increased tariff for customers with low power factor loads. There are lot of technical issues associated with operating at poor power factor like now a part of transmission line capacity is utilized in transporting reactive power which in unnecessary. Losses in transmission lines and transformers increase. Low power factor also tends to be associated with other negative attributes for a well-behaved electrical load. Highly-distorted current waveforms drawn from the mains can inject high- order harmonics back into the supply grid. If we just consider about sinusoidal lagging current, problem of poor Power Factor (or displacement factor) can be improved by many ways. Few of them are by using fixed and variable capacitor bank, over excited synchronous motor and using active filters like STATCOMs.

Now we know that we need the power factor improvement. Most common practice of improving the power factor (word power factor is used here for Displacement Factor) is using variable capacitor. Usually a zero-crossing detection circuit is used for sensing the phase difference between the voltage and current. A controller keeps on switching the capacitor till both phase difference is zero or minimum possible. However, there are some negative impacts associated with power factor correction using capacitor bank.

3.2 Change in THD with change transmission line capacitance

Objective of this experiment is to demonstrate the change in THD in voltage when a capacitor bank is switched on to improve the power factor. Suppose a lagging load is connected in parallel with nonlinear load. There is always a finite amount of inductive reactance present in network and as we demonstrated in previous experiment that if a nonlinear load is present, harmonics appears at PCC voltage. As capacitor bank is switched on to improve the power factor, though the Displacement Factor (cosø) improves but the THD in both voltage and current increases. This leads to degrading distortion factor. Reason behind increased THD in voltage and current is low impedance path offered by capacitor to the higher order currents. Since the impedance offered by capacitor is inversely proportional to frequency so small impedance path is seen by PCC voltage harmonics appeared because of grid inductance & nonlinear load. Now capacitor is sinking high frequency currents which ultimately worsen the THD in voltage and line current.

IV. EXPERIMENTAL SET UP

The Fig. 4 given below shows the line diagram of grid tied system with PCC. The grid tied system consists of a standalone inverter with battery. A voltmeter and an ammeter are connected to measure the panel output voltage and current respectively. The AC output of the grid tied inverter is connected to the point of common coupling (PCC) through a power analyzer. The power analyzer measures the power delivered by panel into the grid. A standalone inverter, connected to a battery bank through a voltmeter and ammeter, acts as a virtual grid for the system. The battery bank is charged through a battery charger using single phase AC as input. The output of the standalone inverter is connected to an auto transformer which is used to adjust the voltage level of the virtual grid. An inductor is connected in series in the system to depict the effect of transmission line inductance present in a real power system. A current sensor and voltage sensor are connected to observe the current and voltage waveform present in the grid. A power analyzer is then connected before the point of common coupling (PCC) to measure the flow of power to and from the grid. At PCC a capacitor bank is also connected through a multiple throw switch for power factor improvement. At the output the load is connected through an output ammeter and a voltmeter. Laboratory scale experimental setup is shown if Fig. 5.

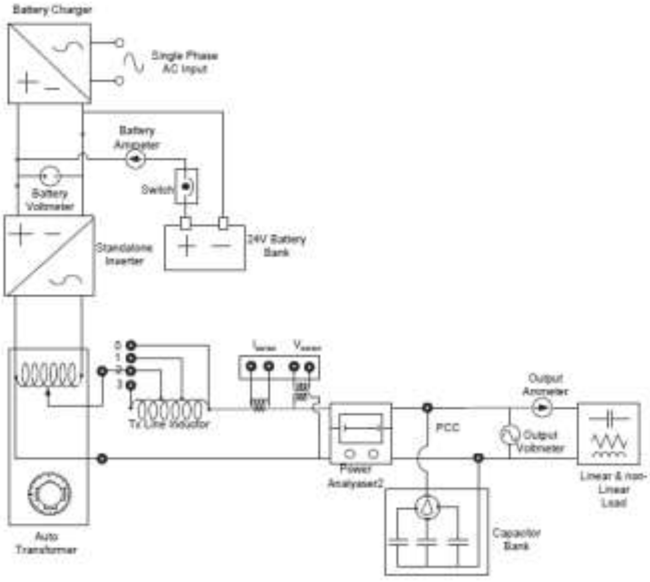

Fig. 4 Block diagram of Grid tied system with PCC

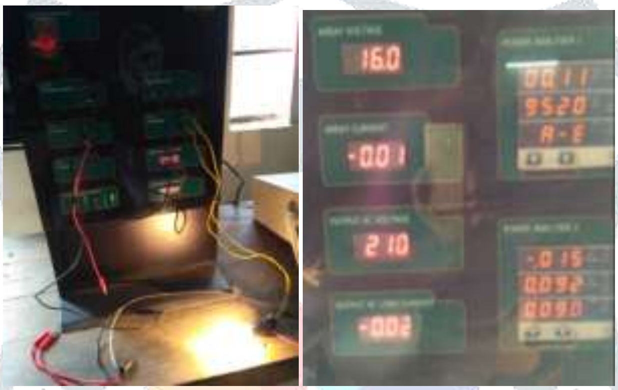

Fig. 5 Laboratory scale experimental setup

4.1 To measure the Voltage at PCC due to transmission line inductance

There are 4 connector ports available for Tx Line inductance marked as 0, 1, 2,3. Inductance used in having 3 terminals and 1 common. Inductance values available are 1mH, 3mH and 6mH and are connected to terminal marked as 1, 2 and 3 respectively. Common point is connected to the terminal 0 and at the same time is connected to phase of PCC also. Usually the transmission line inductance is not that high, however higher inductance values are taken for sake of clear changes in two readings. Connect the Auto transformer output to the PCC taking Tx Line inductance in series. First connect the phase of autotransformer (red connector) with 0 terminal of TX line inductance and connect the ground of auto transformer directly to the PCC ground. Common of TX line inductance is internally connected to the phase terminal of the PCC. Now change the knob of autotransformer to adjust the voltage at PCC equals to 223V rms. Use Power Analyzer 2 to take down all readings. Connect a bulb of 100 Watt to the socket and turn on the switch. Socket is internally connected parallel to the PCC terminal. Take down the reading of voltage. There must be some dip in voltage. This dip occurs because of voltage drop across the inductance of autotransformer. Now turn off the switch. Shift the connection from 0 numbered terminal to 1 numbered terminal of Transmission Line Inductance. This way we have included the 1mH transmission line inductance in addition to autotransformer inductance. Now turn on the switch and observe the voltage at PCC which will be lower than last reading. Same way shifts the connection for transmission line inductance from 1 to 2 numbered terminal and observe the voltage at PCC (Now additional inductance is 3mH). Finally shift the connection from 2 to 3 numbered terminal and observe the voltage at PCC (Now additional inductance is 6mH).

4.2 To measure the PCC Voltage THD and Current THD due to transmission line inductance

Do the same setup as done previously i.e. terminal numbered 0 connected to auto transformer, grounds of autotransformer &PCC connected externally and Voltage adjusted to 210V rms. Connect a significance nonlinear load or both linear and nonlinear load to the socket. For example, 100-Watt bulb can be connected with laptop or any another battery charger. Turn on the switch and note down the reading from Power Analyzer 2. Note down Voltage THD and Current THD. This time inductance present in circuit is only because of autotransformer. Now turn off the switch and shift the connection from 0 to 1 numbered terminal of Tx Line Inductance. Take the same readings, i.e. THD in both voltage and current. by shifting the connection from 1 to 2 numbered terminal and then from 2 to 3 numbered terminals. Take the readings from the both cases

4.3 To measure the Voltage THD, Current THD, Displacement power factor (DF) and Power Factor due to transmission line inductance

First connect the phase of autotransformer to 3 numbered terminals of Tx Line Impedance and autotransformer ground directly to the ground of PCC. This way 6mH inductance is connected in series. Do the parallel connections of capacitor bank to the PCC terminals. Capacitor knob can move for four positions including off. Other three positions connect 0.75µF, 1.5µF and 3µFcapacitors to PCC.

Connect a lagging load like single phase induction motor operating at poor power factor and a nonlinear load like laptop charger to PCC through socket. Keep the capacitor bank knob and the load socket switch off. For waveform observation, connect the oscilloscope channels to the VSENSE & ISENSE. Now rotate the autotransformer knob to adjust the PCC voltage at 210V rms. Use Power Analyzer 2 for taking the reading. Note down THD in voltage & current, phase angle and calculate cosØ. Also observe the waveform of voltage and current in oscilloscope. It can be seen that the current is lagging and at the same time is distorted. Now rotate the autotransformer knob to make voltage zero again. Change the capacitor bank knob to first position. Now capacitor connected is 1.5μF and adjust the voltage slowly to 210V rms. Repeat the Step no 2 by changing the capacitor from 1.5μF to 3.0μF and then from 3.0μF to 6.0μF.

SPECIFICATION

Table I

Standalone Inverter & Battery Charger Specifications

Sr. No.	Parameter	Rating
1	Output Power	750VA/500 W
2	Nominal Output Voltage	230V AC
3	Input Voltage Range for Battery Charging	160-286V
4	2 Batteries	12V, 7.5Ah (each)

Table II

Specification of Inductance and Capacitance

Sr. No.	Parameter	Rating
1	Inductance	1mH, 3mH, 6 mH
2	Capacitance	1.5 μF, 3 μF, 6 μF

Table III

Charge Controller

Sr. No.	Parameter	Rating
1	Maximum Input Voltage	150 V
2	Maximum Output Battery Charging Current	10 A
3	Output Voltage in Automatic Mode	78V
5	Gate Voltage for Manual Mode	5V peak

V. EXPERIMENTAL RESULT AND DISCTION

5.1 Result for Transmission line Inductance

Voltage at PCC and voltage sag at different inductance for linear and non linear load find out from Fig. 3. As per result observation in Table IV, voltage before loading is fixed 223 V. But after adding inductance in transmission line, voltage is reduced at PCC. When there is no inductance in transmission line, voltage sag is very low in case of linear load. But transmission line inductance added 1mH, 3 mH and 6 mH then voltage sag is becoming 2.3 V, 2.6 V and 2.8 V respectively in case of linear load. In case of non linear load voltage sag is large as compare to linear load, when there is no inductance in transmission line. And voltage sag continuously increases after adding inductance 1mH, 3 mH and 6 mH.

Table IV

Result Table for Voltage Sag

Load Type	Voltage Before Loading (volt)	Inductance (mH)	Voltage at PCC (volt)	Voltage Sag (volt)
Linear	223	0	221.7	1.3
	223	1	220.7	2.3
	223	3	220.4	2.6
	223	6	220.2	2.8
Non Linear	223	0	218	5
	223	1	217.5	5.5
	223	3	216.6	6.4
	223	6	216.2	6.8

As per Fig. 6 to Fig. 8, waveform find out from DSO connected at V_{sense} and I_{sense} hardware kit. In Fig. 4, PCC voltage is sinusoidal due to there is no inductance in line. In case of linear load when inductance in transmission line is connected, voltage at PCC reduced due to voltage sag as per fig. 4. As per fig. 6, large voltage sag at PCC is produced due to non linear load.

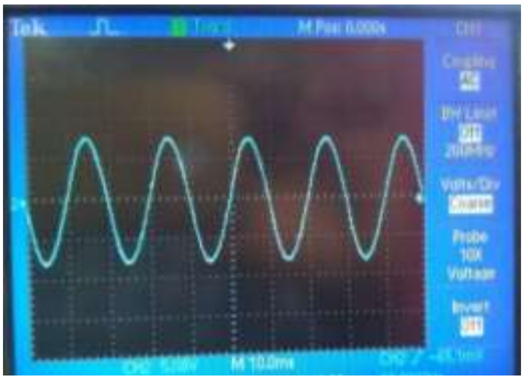

Fig. 6 Wave form of voltage at PCC, when no inductance in line

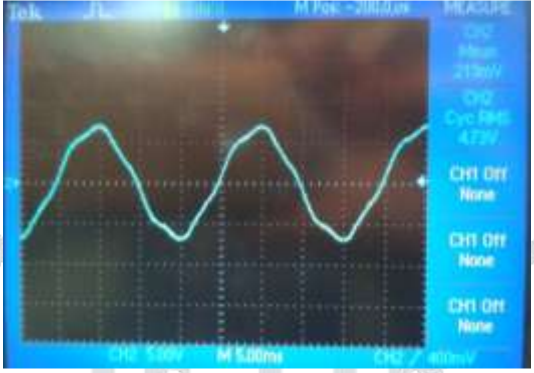

Fig. 7 Wave form of voltage at PCC due to effect of inductance in linear load

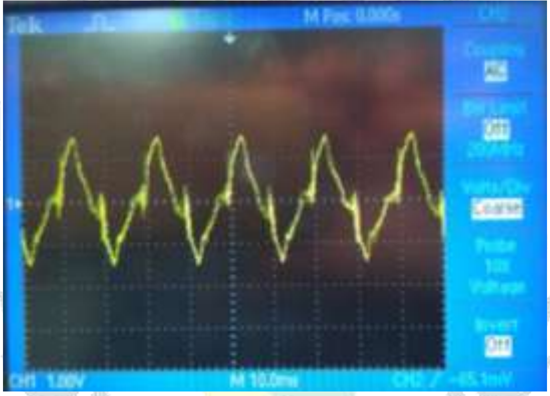

Fig. 8 Wave form of voltage at PCC due to effect of inductance in non linear load

Result of THD voltage and current at PCC is find out as per Table V. When transmission line inductance increases, in linear load, THD voltage increases and THD current reduces at PCC. But in non linear load, THD current higher as compare to linear load.

Table V

Result Table for Change in THD with Change in Transmission Line Inductance

Load Type	**Inductance (mH)**	**PCC voltage THD**	**THD Current**
Linear	0	4.70	4.82
	1	4.69	4.77
	3	4.67	4.7
	6	4.61	4.68
Non Linear	0	4.87	14.44
	1	4.917	15.8
	3	4.958	15.99
	6	5.063	16.10

5.2 Result for Transmission line Capacitance

Result for Voltage Sag and Power factor is given in Table VI. Voltage before loading is fixed 223 V. But after adding capacitance in transmission line, voltage is reduced at PCC. Transmission line capacitance is added 1.5 µF, 3 µF and 6 µF then voltage sag is becoming 2.2 V, 2.6 V and 2.8 V respectively in case of linear and non linear load. So, when transmission line capacitance increases, voltage at PCC reduces. So, voltage sag is also reduced. So as per Fig. 9, voltage is higher due to capacitance in transmission line. Result for Change in THD with Change in Transmission Line Capacitance is find out in Table VI. When transmission line inductance increase, THD voltage and THD current both are reduced.

Table VI
Result Table for Voltage Sag and Power factor

Load Type	PCC voltage THD	Current THD	Capacitance (μF)	Power Factor
Linear & Non Linear	4.572	30.22	0	0.37
	4.583	33.03	1.5	0.6
	4.599	33.18	3	0.73
	4.675	37.51	6	0.91

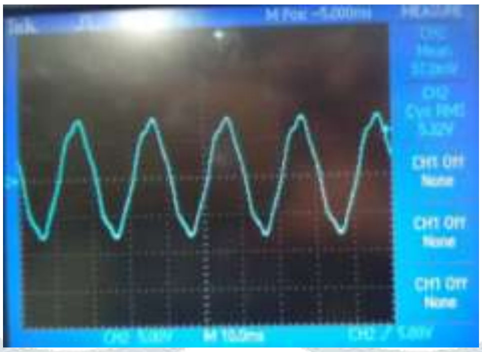

Fig. 9 Wave form of voltage at PCC due to effect of capacitance in linear & non linear load

VI. CONCLUSION

Based on reading taken of transmission line inductance, with fixed voltage power source and with current, voltage changes as inductance of transmission line changes. Since inductance is function of length, voltage values are different at different lengths in transmission line. This is the reason why voltage dips more in remote areas. Secondly by changing the load from 100W to 200W and then to 300W, it can be observed the voltage sag is higher at PCC when load connected is higher. This phenomenon can be usually observed in industrial areas where bulb brightness fluctuates when an arc welding machine is operated. It can be observed that THD in voltage increases whereas the THD in current decreases as inductance increases. It can be seen that though the angle between voltage and current is decreasing or now current is becoming from lagging to leading (based on load rating), the THD in voltage and current is increasing at the same time. Using capacitor solves one part and contributes to other problem.

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