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Research paper

Techno-economic analysis of Smart Grid pilot project- Puducherry

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Abstract

Smart Grid (SG) a well-known concept being rapidly introduced in the power industry. New transformation of Indian power network has begun with 14 SG pilot projects across the nation. One of such projects has been successfully commissioned in Puducherry. The motive of this research work is to analyze the techno-economic aspects of a smart distribution network before being implemented nation-wide the study case facilitating efficient planning and deployment of technology. This paper presents techno-economic analysis of Smart Grid via a case study of Puducherry pilot project. Covered in this paper are different components of investment which convey an idea about services and their proposition as well as technical advancements with their benefits. This paper discusses the gain in terms of energy and money saving through different smart technical tools. Payback analysis explains how investment in smart distribution network is justified.

Keywords: Smart grid; Green energy; Grid infrastructure; Stability; Regulation

1. Introduction

Electric power has become a backbone to economic growth of any nation, across the globe. World's electrical energy production in 2014 was 22,433 TWh, out of which 66% was from coal, gas and oil [1]. Existing fossil fuel based power infrastructure is bulky, complex and non-eco-friendly. In Ref. [2], Global smart grid federation (GSFG) explained how the existing power grid network is not capable to meet the requirements of 21st century. At present, power network structure is in accordance with the concept of centralized power generation. Smart grid (SG), the new facet of power infrastructure, facilitates the decentralization of power generation [3]. Smart grid has shown its competence to meet power availability, reliability, quality, economic operation, efficiency, safety, security and other essential parameters along with the environmental issues [4,5].

India has an installed capacity of more than 280 GW [6], and has opted for smart grid to meet the power deficiency, green energy challenges and other needs of the country [7–9]. Concept of smart grid, its technologies, challenges and difficulties in implementation have been discussed in detail on several platforms [10–17]. With the approval of the Indian Government, fourteen smart grid pilot projects are being developed across the country [18]. Under such circumstances, techno-economic analysis of smart grid pilot projects becomes very essential. A study has been carried out on Puducherry smart grid pilot project, jointly developed by Power Grid Corporation of India Ltd (PGCIL) and Puducherry Electricity Department (PED), to understand its techno-economic aspects [19,20]. The pilot project has completed its interim stage and is operating with a good power quality [21]. Rooftop solar PV systems with net metering facilities were also installed in this pilot project [22] to show-case the integration of clean energy solutions [23–28].

The main motivation for this work is to better understand the techno-economic issues of a smart grid infrastructure for future advancement of SG technology and the expansion of such pilot projects across the country [29]. For effective planning, it is essential to understand both the positive and negative aspects of the SG technologies. Implementation of any technology reflects in terms of investment sought and its success is measured by profit gained by both investor and the society. This paper is organized in a manner that Section 2 discusses about the features, factors and investment of Puducherry SG pilot project. Section 3 deliberates the advanced features in detail which is followed by the techno-economic studies in Section 4. Section 5 explains the payback analysis.

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Nomenclature

SG	Smart Grid
GSFG	Global Smart Grid Federation
TWh	tera watt hour
GW	giga watt
PGCIL	Power Grid Corporation of India Limited
PED	Puducherry Electricity Department
kV	kilo volt
kVA	kilo volt ampere
kVAr	kilo volt ampere reactive
VAr	volt ampere reactive
MVA	mega volt ampere
A	ampere
THD	total harmonic distortion
IGBT	insulated gate bipolar Transistor
km	kilo meter
AMI	advance metering infrastructure
PQM	power quality management
OMS	outage management system
PLM	peak load management
EV	electric vehicle
DT	distribution transformer
LT	low tension
CT	consumer terminal
JERC	Joint Electricity Regulatory Commission
TOU	time of use
PLM	peak load management
APFC	automatic power factor compensation
OMS	outage management system
DTMS	distribution transformer monitoring system
FPI	fault passage indicator
CT	current transformer
PT	potential transformer
SMS	short messaging service
SLA	street lighting automation
MU	mega unit
$	American Dollar
O&M	operation and maintenance
PWV	present worth value
PWF	present worth factor
IF	inflation rate
IR	interest rate
F&I	fixing and installation
RoI	return on investment
AT&C	Aggregate Technical and Commercial

2. Project infrastructure

Puducherry SG pilot project has been developed in division-1 of Puducherry that has 100% electrification with 7 nos. of 22 kV feeders and 5 nos. of 11 kV feeders. Pilot project covers around 1400 consumers connected to 9 distribution transformers of a 22 kV feeder. The feeder comprises sections of overhead lines and underground cables whose lengths are 9.11 km and 3.83 km respectively.

Table 1
Investment in Puducherry SG pilot project.

Field requirement	Total in $
Single phase services	2,686,449.60
Three phase services	2,149,159.68
DCU and routers	298,494.40
Sub-total-I	**5,144,550.98**
Taxes (F&I at 6% + Entry taxes at 8% + Erection charges at 10%)	1,231,289.40
Total-I (including taxes)	**6,365,393.08**
Control room requirement software:	0
MDAS head end	111,935.40
MDM	186,559.00
Software license – Server OS + Anti- virus + Database	164,171.92
External network and data security for integrating MDAS, MDM with consumer portal and billing	34,326.86
Sub-total-II	**496,993.18**
Taxes (F&I at 6% + Entry taxes at 8% + Erection charges at 10%)	117,905.29
Total-II (including taxes)	**616,241.69**
Total Cost	**6,981,784.02**

In the pilot project, all the components of SG such as advance metering infrastructure (AMI), power quality management (PQM), outage management system (OMS), peak load management (PLM), renewable energy integration, electric vehicle (EV), etc. have been deployed. The investment of this pilot, for 40,000 consumers is $6,981,784.02. The consumers comprise 60% single-phase and 40% three-phase connections. From a total investment of $6,981,784.02, the field requirements account for $6,365,393.08 while the rest account for the control room and software requirements. A brief summary of the same is given in Table 1 field requirements including smart meters and other devices for both the single and three phase services of pilot area.

3. Smart grid project infrastructure

Smart grid technology incorporates multiple advance features in power network to improve the efficiency of the system. Few advance features of the Puducherry smart grid pilot project are as follows.

3.1. Energy audit

Smart distribution network of Puducherry has been equipped with AMI, DCU, GIS, advance communication network and other hardware/software tools that enable smart grid operators to perform on-line energy audit of the system. Fig. 1 shows the location of devices installed in the project area. Using online energy audit, operators can determine the technical and commercial losses of the feeder, at any instance. Amount of un-accounted energy can be reduced by taking preventive actions. Energy audit was carried out leveraging hourly data of DT meter (LT CT meter) and hourly data of all consumers under each distribution transformer.

Monthly energy audit of consumers connected to a distribution transformer has been performed and details are as shown in Fig. 2. As shown in the figure, the difference of DT energy meter and energy consumed by customers of the DT was found

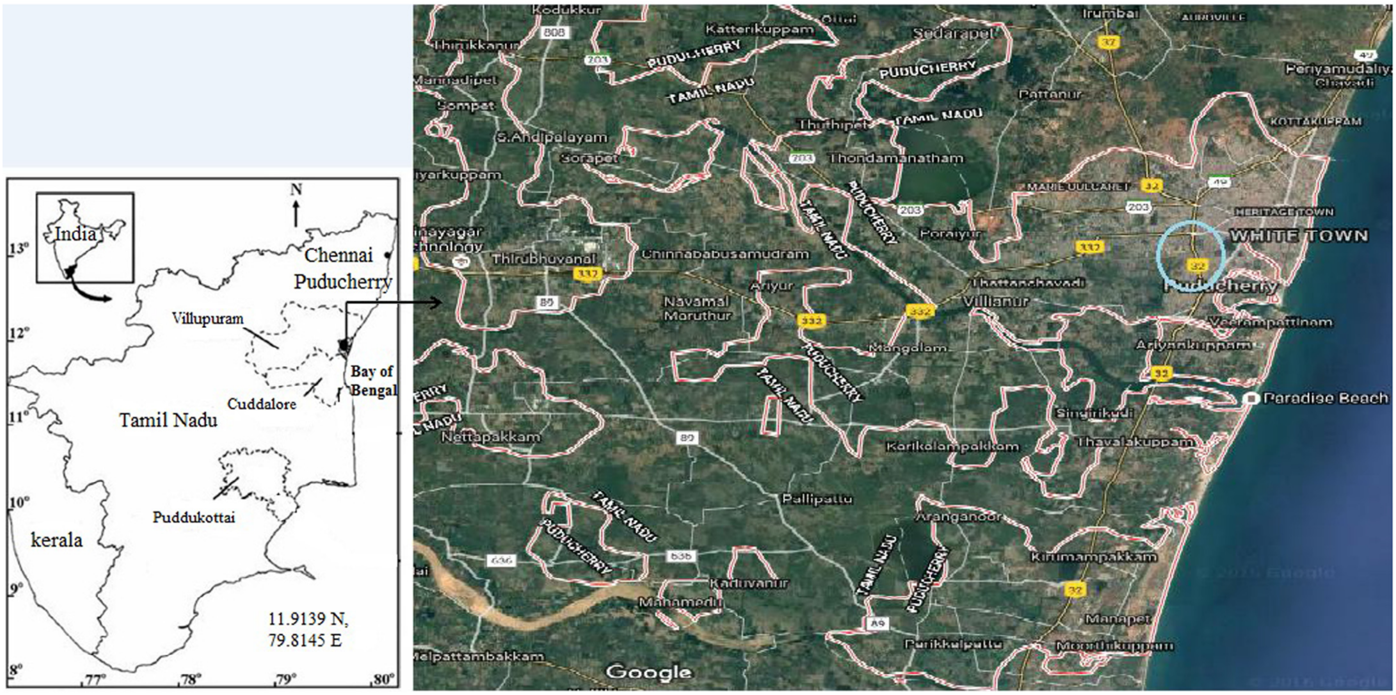


Fig. 1. Locations of smart meters, DCU, APFC and DTs in Puducherry.

to be in the range of 7–11%. This clearly shows that losses due to un-accounted energy could be reduced up to 11% through smart meters.

3.2. Net metering

Puducherry SG pilot project has been integrated with a rooftop solar PV system through a smart meter which has a net metering facility. With rooftop solar integration, power could flow in either direction. Smart meters are capable of metering this bidirectional power flow and net energy is computed by these meters at the consumer premises. Smart meters installed in Puducherry are capable of measuring all three components of energy i.e. kWh, kVArh and kVAh. These meters store energy reading at intervals of 30 minutes and above. Further, these meters are also equipped with suitable communication devices for two-way communication with control center, to transfer data and receive control commands.

Fig. 3 shows monthly net meter profile for a consumer. Composition of import and export of active component of energy is shown in Fig. 3a. Net kWh curve is the difference between import kWh curve and export kWh curve. Positive portion of net kWh plot signifies that on an average, consumer has drawn more power from grid than injected into it while negative portion signifies that injected power into the grid is

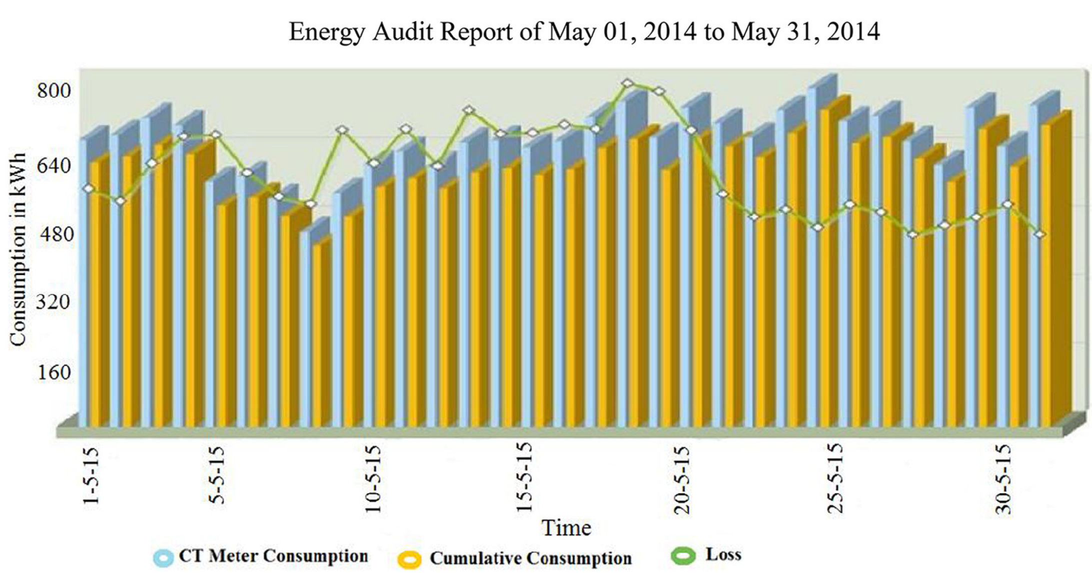
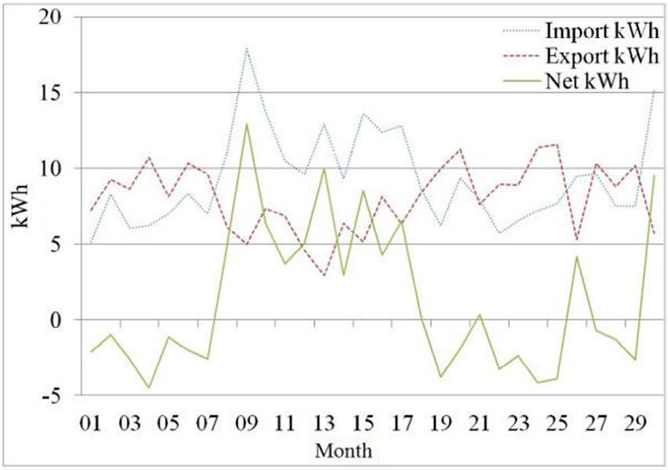


Fig. 2. Monthly energy audit of DT.



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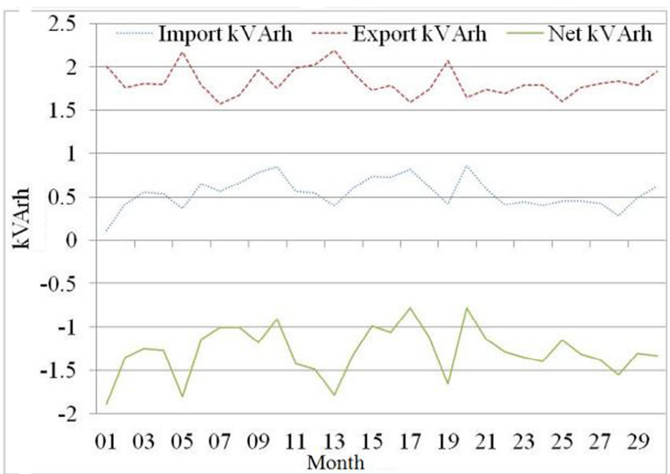

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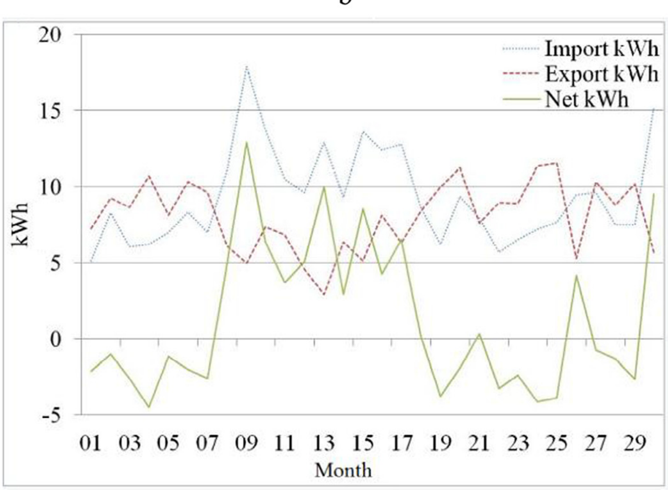


c

Fig. 3. a. Monthly import, export and net kWh data of a selected net meter. b. Monthly import, export and net kVAh data of a selected net meter. c. Monthly import, export and net kVAh data of a selected net meter.

more than the power drawn from the grid. It is clear from Fig. 2 that for almost 16 days of the month, consumer has injected more power than the quantum of power drawn from the grid. Similarly, Fig. 3b and Fig. 3c presents the composition of import and export of reactive and apparent components of energy respectively [30]. From Fig. 3b, it is interesting to note that the consumer has injected more reactive power to grid than it is drawn from the grid for the entire month.

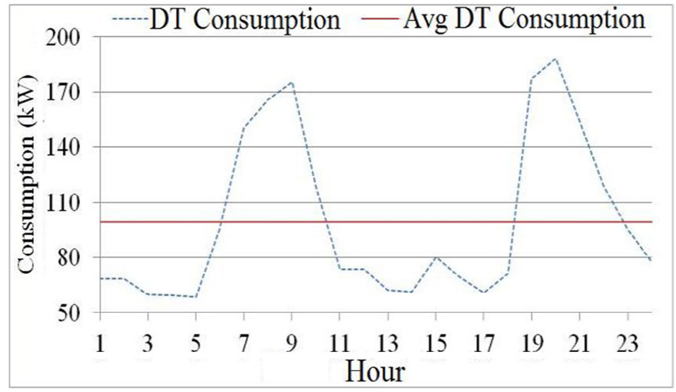


Fig. 4. Hourly real power profile of a DT.

3.3. *TOU tariff*

Smart grid incorporates multiple advance technologies that enable real time monitoring and control of power. This advancement facilitates the operators with the ability to introduce different tariff structures to support demand response and demand side management. Joint Electricity Regulatory Commission (JERC) of Union Territory of Puducherry has recommended the time of use (TOU) tariff. Consequently, price of electricity varies with the time of utilization. Hence, a tariff structure with higher charges during peak hours and lower charges during off peak hours can be applied for better load management. Fig. 4 shows the hourly real power profile of a distribution transformer of a town feeder for a specific day, from which it can be observed that the average consumption for the day is 99.34 kWh while peak consumption is 188.23 kWh which is 189.4% of the average consumption. Implementation of TOU tariff could help in shifting load on DT from the peak load period to off peak periods. This shifting has the potential to increase the performance of the system, as maximum power flow in the network would be reduced. Further, overall price of energy for a consumer would reduce if the consumer opts to shift usage from peak to off peak periods.

4. Techno-economic analysis

4.1. *Peak load shaving and metering efficiency*

Energy shaving through peak load management (PLM) is a major achievement of SG. It refers to shavings of energy during peak hours by shifting loads from peak periods to off peak periods. Figs. 4 and 5 show hourly load profile of SP Nagar DT and two consumers, respectively. Also the peak hour consumption for three consumers and DT with respective possible saving percentage during peak hour consequent to PLM is as shown in Table 2.

From the analysis, one can conclude that average demand for consumer 1 is mere 0.98 kWh while the maximum peak

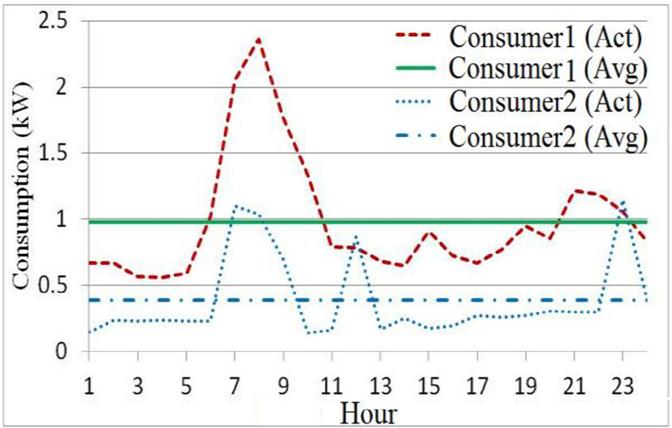


Fig. 5. Hourly consumption profile of two consumers on DT.

demand attains the value of 2.366 kWh. Maximum peak demand is 241.42% more than the average demand throughout the day. Daily energy requirement of consumer 1 is approx. 23.5 kWh and through PLM, maximum reduction that could be achieved is 58.58% on its peak demand. Average reduction achieved is 28.8% and average demands of consumers 2 and 3 are only 0.39 kWh and 3.411 kWh respectively; while their respective maximum demands are1.15 kWh and 9.0234 kWh that are 294.87% and 264.61% more than their respective average demands. Daily energy requirement of consumer 2 is 9.36 units and the same for consumer 3 is 81.864 kWh. PLM provides an opportunity to reduce consumption on peak demand up to 66.09% for consumer 2 and up to 62.20% for consumer 3. Average peak shaving is 59.35% and 45% respectively for consumer 2 and consumer 3. Analysis on SP Nagar DT reveals (from data in Table 2 and Fig. 4) that maximum demand recorded is 188 kWh which is 189.48% more than the average demand of 99.34 kWh and average peak shaving that could be achieved on SP Nagar DT through group level control is 34.66%.

Table 2
Energy saving through peak load management.

Hour (of the day)	Actual kWh	Average kWh	Difference (peak-mean)	Shaving
Consumer 1 (average shaving 28.8%)				
6th	1.023	0.98	0.043	4.20%
7th	2.055		1.075	52.31%
8th	2.366		1.386	58.58%
9th	1.765		0.785	44.48%
10th	1.335		0.355	26.59%
21st	1.216		0.236	19.41%
22nd	1.189		0.209	17.58%
23rd	1.059		0.079	7.46%
Consumer 2 (average shaving 59.35%)				
7th	1.1	0.39	0.71	64.55%
8th	1.04		0.65	62.50%
9th	0.7		0.31	44.29%
23rd	1.15		0.76	66.09%
Consumer 3 (average shaving 45%)				
6th	4.79551	3.411	1.3845	28.87%
7th	7.7234		4.3124	55.84%
8th	8.05		4.639	57.63%
9th	9.0234		5.6124	62.20%
10th	7.77409		4.36309	56.12%
19th	3.99172		0.58072	14.55%
21st	6.75426		3.34326	49.50%
22nd	6.29465		2.88365	45.81%
23rd	5.20742		1.79642	34.50%
Distribution transformer (average shaving 34.66%)				
7th	150.5	99.34	51.16	33.99%
8th	165.8		66.46	40.08%
9th	175.4		76.06	43.36%
10th	119.196151		19.85615	16.66%
19th	177.430304		78.09030419	44.01%
20th	188.236		88.896	47.23%
21st	153.655601		54.3156	35.35%
22nd	119.196151		19.85615	16.66%

Analysis of the data suggests huge scope for load management, peak shaving and energy saving by shifting loads from peak period to off peak periods. Peak load management is beneficial for both the small and large consumers as well as utility operators. Availability of such data encourages consumers to opt for PLM and reduce their energy consumption and consequently by the electricity charges. System operators could also avail the opportunity to increase operating capability and the efficiency of the system. The expenditure on purchasing costly peak power from other utilities gets reduced and the incidental losses are avoided by adopting such efficient load management techniques, besides achieving enhanced system stability and reliability.

The improvement in the efficiency in metering, when the conventional rotating type standard meters are replaced by smart meters, is presented in Table 3. The readings have been recorded between 17th April 2014 and 3rd September 2014 (about 4.5 month) for a group of 30 consumers.

4.2. Billing efficiency

Smart meters acts as a backbone in the development of smart grids. As mentioned earlier, large number of smart meters have been installed in the pilot project. These smart meters have made billing, free from manual intervention. Traditional billing cycle in Puducherry is of 20 days, in which a person goes from door to door to note down the meter readings. The billing is done at a single time at the end of the month. However, the installation of smart meters has reduced this billing cycle from 20 days to 30 minutes in Puducherry smart grid Pilot Project. Further, billing can also be done for any number of consumers and at any number of times with the desired frequency of time durations viz. peak, off-peak, etc. The cost of collecting meter data has reduced from $2.24 per consumer to zero. For 40,000 consumers, the total reduction of the billing cost is $89,548.32. Apart from the improvement in the billing efficiency the accuracy of the billing has also been increased, as errors incidental to manual intervention have been reduced. Further, the web service provided in the smart grid enabled the online payment of electricity usage charges by the consumers through online banking portals. Analysis of Table 3 reveals significant difference between readings from existing traditional meters and from the smart meters installed for the same consumer. Aging is the main cause for fall in accuracy of existing meters. During

Table 3
Comparison of existing traditional meters and smart meters.

Consumer no.	Consumption units between 17/04/14 to 03/09/14 (in kWh)		Difference %
	Traditional meter readings (kWh)	Smart meter readings (kWh)	
1	0	480.2	100
2	0	3008.6	100
3	174	175.0	0.55
4	0	116.2	100
5	364	362.7	−0.37
6	0	806.8	100
7	0	1177.4	100
8	1301	1317.3	1.24
9	1393	1398.2	0.37
10	0	1702.4	100
11	0	1815.0	100
12	0	1062.8	100
13	0	2830.7	100
14	0	3072.8	100
15	0	713.8	100
16	141	2329.2	93.95
17	0	772.2	100
18	919	924.4	0.58
19	0	2.8	100
20	823	825.4	0.29
21	471	477.7	1.40
22	1249	1252.0	0.24
23	0	3614.2	100
24	0	737.3	100
25	0	262.9	100
26	266	721.3	63.12
27	0	2280.8	100
28	0	778.2	100
29	0	393.2	100
30	2509	2856.7	12.17

this project, many existing meters (19 out of 30) were found to be stuck, which also lead to high inaccuracy in metering and accounting. It was found that none of the existing meters were found as accurate as the smart meters. Out of eleven existing meters in operation, 10 meters have recorded lesser amount of energy consumption than the actual, while one meter was found to have recorded 0.37% higher value than the actual [31].

In another observation done over a month, it has been found that metering efficiency is around 12 to 14%, when 25% of stuck meters were not considered. Improvement in efficiency achieved could be 65%, if stuck meters are also considered. Table 3 presents the severity of ill metering in Indian scenario bringing out the importance for a pathway, where by a large section of commercial losses can be reduced by deploying smart meters.

4.3. Power quality

The concept of Smart grid enables the integration of renewable resources via power electronic devices. These interventions inject harmonics into the system and may lead to the deterioration in power quality. Different parameters and standards of power quality are described in Ref. [21]. Puducherry SG pilot project uses automatic power factor correction (APFC) devices and active filters for improving the power factor and power quality. Installed APFC in Puducherry has a total VAr compensation capacity of 140 kVAr in steps of (50 + 50 + 20 + 10 + 10). Fig. 6 shows the daily compensation graph for the APFC device. The device has been found compensating 23.1 kVArh on an average, while maintaining the average hourly power factor above 0.99 throughout the day. Installed APFC device is equipped with a communication device that is configured for hourly reporting to the control center.

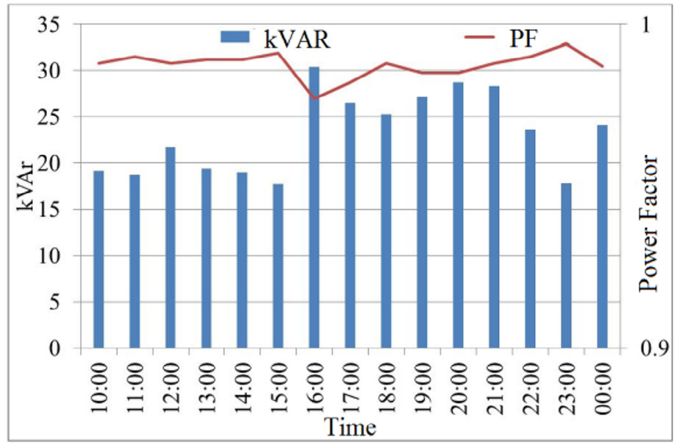


Fig. 6. Automatic power factor correction.

The installed active filters are IGBT based and its total capacity is 150kVA and it provides a smooth control over the entire range. These active filters are capable of eliminating harmonic distortion, neutral compensation, power factor correction at load side through the reactive power compensation and voltage compensation. Table 4 presents the data of neutral current compensation through active filter. It can be observed that neutral current, which used to be 146.5A during peak hours, has been reduced to 92.5A after installing active filter. Similarly during off peak periods, neutral current has been reduced from 128A to 76A after active filter installation. A compensation of 36.8% and 39.2% has been recorded during peak and off-peak periods.

A study has been carried out to determine the power quality of Puducherry SG pilot project. Power quality parameters for SP Nagar DT of rating 315 MVA, 22/0.433 kV have been measured and analyzed. Fig. 7 shows the variation of voltage as 2.9% from the nominal value, much lesser than the maximum limit of 10%. Maximum frequency variation and flicker are recorded to be 0.14 Hz and 0.3 V. Flicker is shown in Fig. 8. Maximum values of voltage THD in phase ABC are 1.326%, 1.24% and 1.32% of voltages respectively, which are as shown

Table 4
Active filter compensation.

	Neutral current compensation (A)		Compensation
	Before	After	
Peak hour	146.5	92.5	36.8%
Off-peak hours	125	76	39.2%

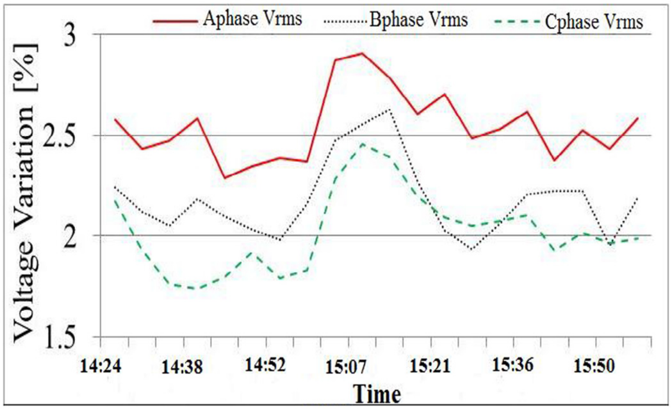


Fig. 7. Voltage variation on SP Nagar DT.

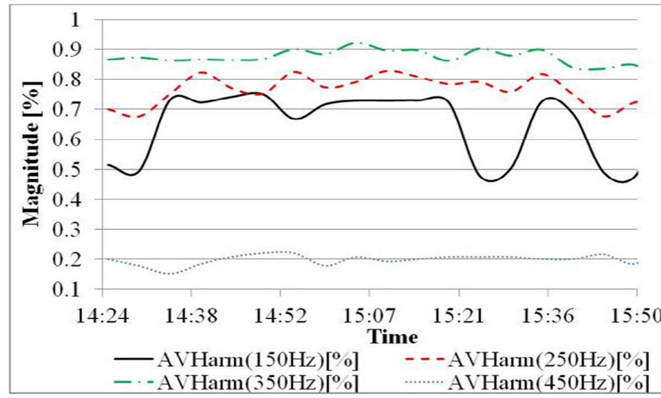


Fig. 10. Individual odd harmonics content in phase A voltage of SP Nagar DT.

in Fig. 9. Fig. 10 shows the harmonics present in phase A voltage of SP Nagar DT. The 7th order harmonics is the highest and attains maximum value of 0.92% followed by 0.83% contribution by the 5th order component. The Maximum contribution of the 3rd and 9th order components are 0.75% and 0.22% respectively. On observations of frequency, voltage, THD, harmonics and flicker parameters for SP Nagar DT of Puducherry SG pilot project it has been found that all the parameters are

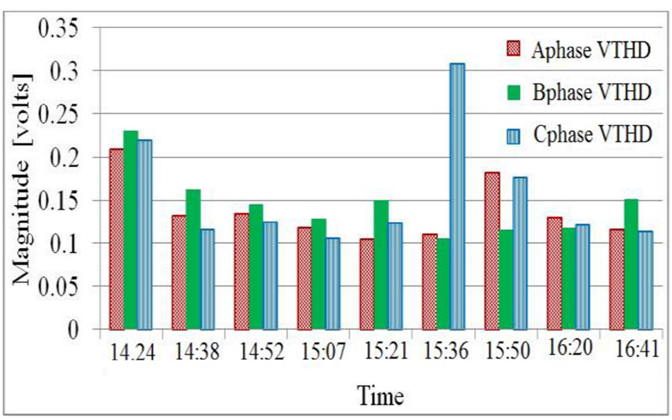


Fig. 8. Flicker in voltage at SP Nagar DT.

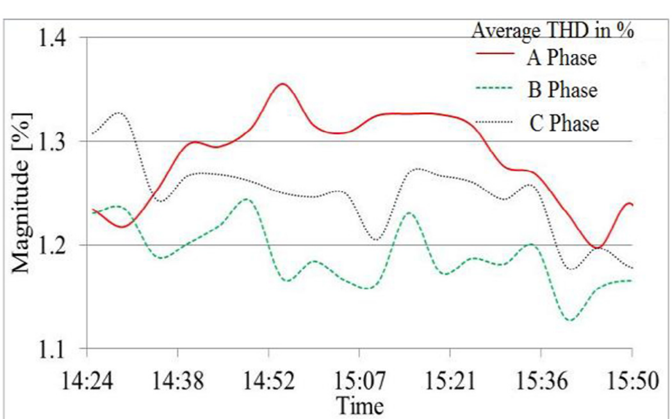


Fig. 9. Average voltage THD of SP Nagar DT.

within the range of defined limits. The analysis reveals good quality power at this DT.

4.4. Outage management system (OMS)

Outage management system (OMS) has the potential of enhancing the reliability of the power infrastructure. As discussed in the literature, smart grid incorporates AMI, DA, ICT and other smart devices into the power network. OMS could utilize this smartness for wide range of benefits like efficient power restoration, reliable and enhanced consumer services, reduced cost etc. [32,33].

In Puducherry SG pilot project, outage management has been achieved with a distribution transformer monitoring system (DTMS) and fault passage indicators (FPI). Table 5 gives the details of DTMS installed in the pilot project. All DTMS systems have been equipped with oil sensors, palm sensors, CT and PT. DTMS are capable of measuring all the phase current loadings, oil level and temperature of DT. Instantaneous current values in a specific DT are as shown in Fig. 11 and the readings are 281A, 254A and 267A for phase A, B and C respectively. Figs. 12 and 13 show the average daily current for 30 days and an average daily load for March 2014, respectively. It has been observed that average currents are between 199A and 339A while average daily percentage loadings are in the range of 29% to 49%. Fig. 14 displays the DTMS system depicting graphs of different temperature profiles (viz. Windings, Oil and Enclosure) of the DT. Fig. 15 shows an FPI installed in Puducherry SG pilot project. In total, 21 numbers of such FPIs have been installed, out of which 6 are equipped with communication devices and 15 are without communication devices. FPIs with communication ability have the facility of

Table 5
Details of DTMS installed in Puducherry SG pilot projects.

Supplier	Sensors		
	Oil temp	Palm	CT, PT
Matrix	Yes	Yes	No
AMI Tech	Yes	Yes	No
Sharika	Yes	No	Yes
SAI Electricals	Yes	Yes	Yes
Gridsense	Yes	No	Yes

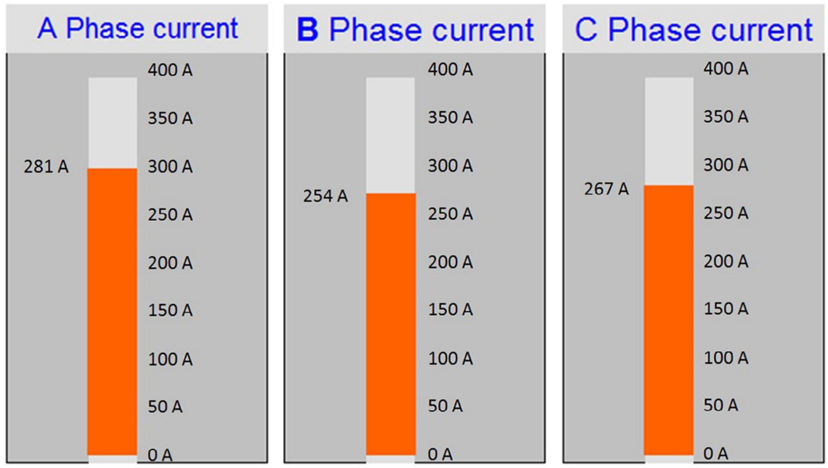


Fig. 11. Instantaneous current of all three phases of a DT.

data access through web link also. Fig. 16 shows a typical message received from an FPI that includes date, time, feeder and other relevant data regarding faults. Table 6 summarizes total number of faults detected by FPI system between July 2014 and November 2014. During this span of 5 months, 26 transient faults and 91 permanent faults are reported by FPI devices. Display monitor for FPI is also shown in Fig. 17 that gives fault data report of OMS which includes date, time, longitude, latitude, type of fault and also the current through conductor.

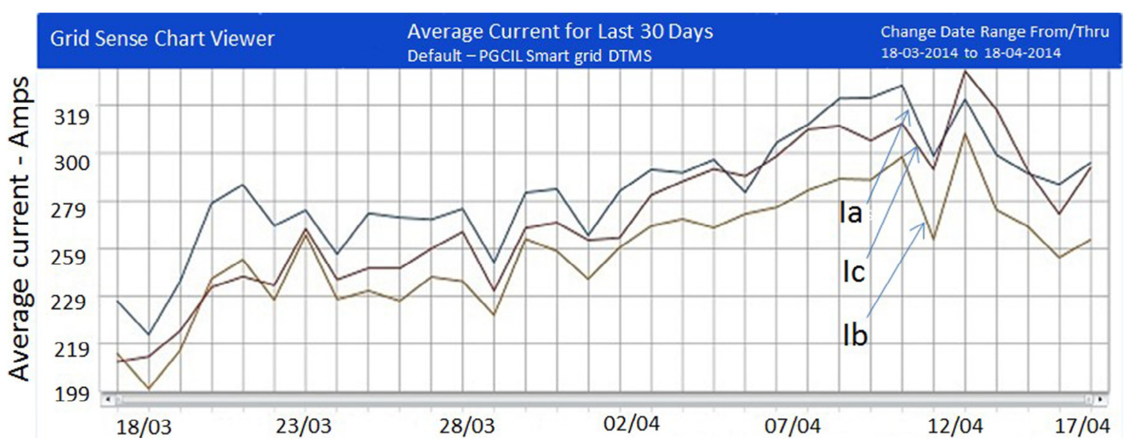


Fig. 12. Average daily current for 30 days.

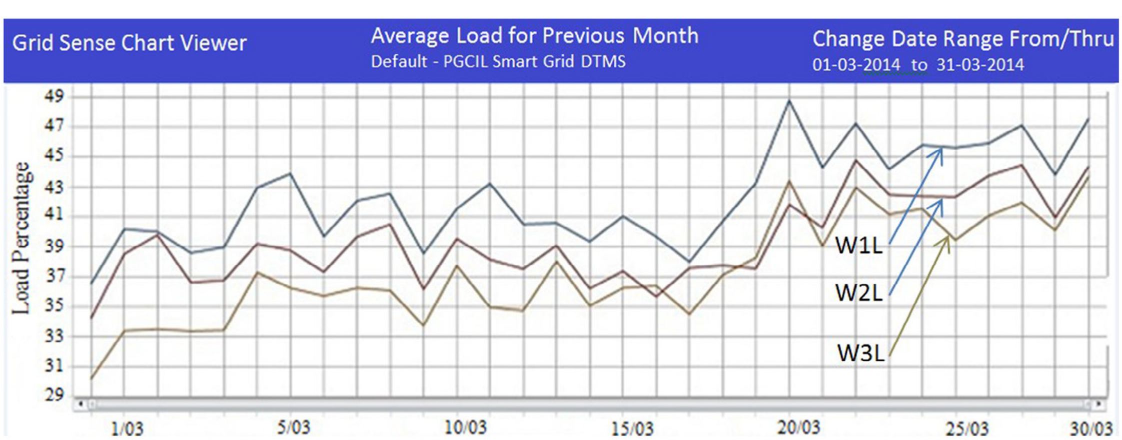


Fig. 13. Average daily percentage loading for March 14.

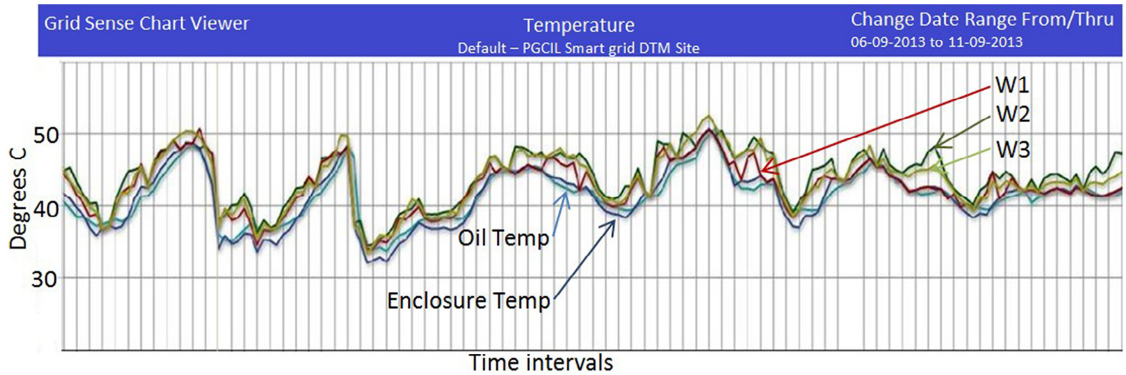


Fig. 14. DTMS display showing different temperature profiles of selected DT.

4.5. Loss detection

In Puducherry SG pilot project, smart meters collect, compute, store and transfer energy data to control center at an interval of 30 minutes. Thus, by comparing the energy data at different nodes and DT terminals, power flows and energy loss have been detected very easily through software. For example, considering SP Nagar DT, if we compare data from DT and cumulative sum of data from each consumer's smart meter connected to DT, the difference would be equal to losses in the system as seen in Fig. 2.

Fig. 15. FPI installed in Puducherry.

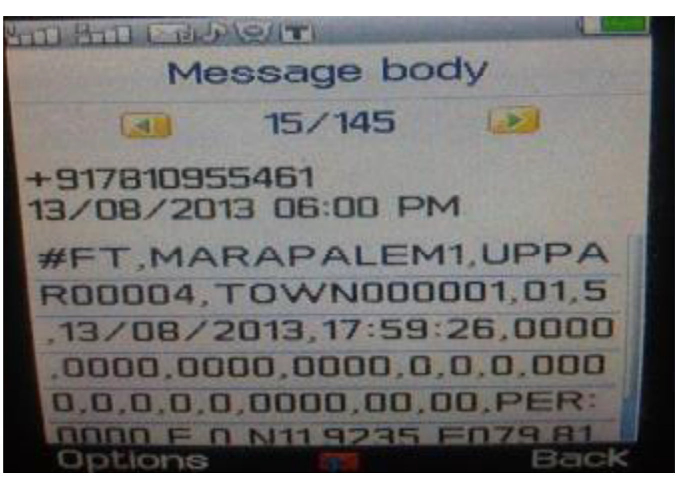


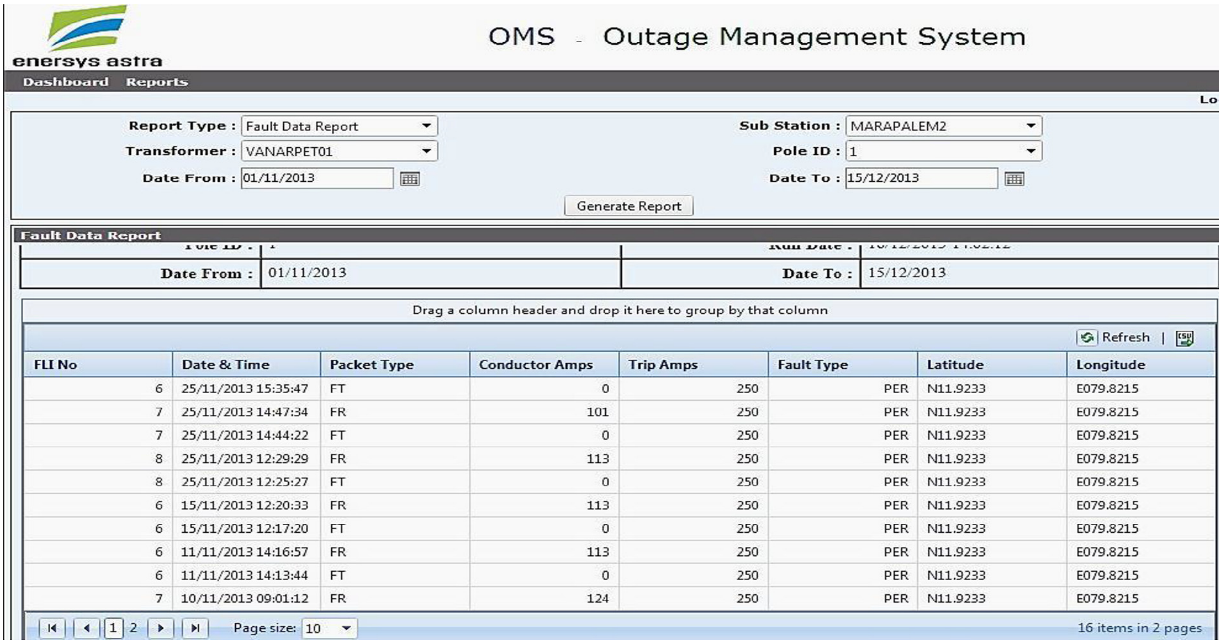
Fig. 16. A sample message from FPI.

4.6. Tamper analysis

Smart meters of Puducherry SG pilot project are tamper proof. Tampering includes any deviation of current from defined limits due to any fault or malpractice or damage to the metering system. These meters are designed in such a manner that on an event of tampering, smart meter itself would send an SMS to server which in turn passes information to the respective individuals via e-mail and SMS alerts. Fig. 18 is an image of a typical tampering alert which includes date, time, area, location, meter details and also the type of tampering. Table 7 shows a short list of few selected tampering events reported through smart metering system. It also includes type of tampering, cause and corrective actions taken up by concerned authorities. Out of eight tampering cases, two correspond to over-current, five correspond to terminal cover open and last one correspond to flow of current through earth. Authorities of Puducherry electricity department (PED) conduct a thorough investigation in response to tampering alerts. It was observed during investigations that one consumer was drawing current more than the connection limit, while in another case, meter itself was found mal-operating. In cases of "opening the terminal cover" kind of tampering, an investigation revealed that three consumers have shifted the location of meters without prior notice to the utility.

Table 6
Details of faults detected by FPI, between July 2014 and November 2014.

Fault	Permanent fault	Temporary fault
July	38	8
August	20	8
September	13	4
October	13	5
November	7	1
Total	91	26


OMS - Outage Management System

Dashboard Reports

Report Type : Fault Data Report
Transformer : VANARPET01
Date From : 01/11/2013
Sub Station : MARAPALEM2
Pole ID : 1
Date To : 15/12/2013
Generate Report

Fault Data Report

Date From : 01/11/2013 | Date To : 15/12/2013

Drag a column header and drop it here to group by that column

Refresh

FLI No	Date & Time	Packet Type	Conductor Amps	Trip Amps	Fault Type	Latitude	Longitude
6	25/11/2013 15:35:47	FT	0	250	PER	N11.9233	E079.8215
7	25/11/2013 14:47:34	FR	101	250	PER	N11.9233	E079.8215
7	25/11/2013 14:44:22	FT	0	250	PER	N11.9233	E079.8215
8	25/11/2013 12:29:29	FR	113	250	PER	N11.9233	E079.8215
8	25/11/2013 12:25:27	FT	0	250	PER	N11.9233	E079.8215
6	15/11/2013 12:20:33	FR	113	250	PER	N11.9233	E079.8215
6	15/11/2013 12:17:20	FT	0	250	PER	N11.9233	E079.8215
6	11/11/2013 14:16:57	FR	113	250	PER	N11.9233	E079.8215
6	11/11/2013 14:13:44	FT	0	250	PER	N11.9233	E079.8215
7	10/11/2013 09:01:12	FR	124	250	PER	N11.9233	E079.8215

1 2 Page size: 10 16 items in 2 pages

Fig. 17. Fault data report of OMS.

One consumer has connected welding machine and another one has bypassed the meter. Investigations on "load through earth tampering" revealed a damaged wiring inside the house.

4.7. Street light automation for energy saving

Puducherry SG pilot project had also implemented a street lighting automation (SLA) scheme to reduce energy consumption. A total of 136 number of street lights from three suppliers have been installed. Thirty street lights have been equipped with a on/off timing control with an ability to synchronization of time with an astronomical clock. Voltage dimming facility based on time-setting and traffic condition is also available. Further, each lamp has been facilitated with elements for power factor improvement. Energy saving of 57% has been realized through this group of street lights. In addition, individual lamp control is also provided. Through this initiative, street lights have contributed to energy savings. Fig. 18 presents the impact of SLA installation. It is clear from the graphs that energy consumption is reduced by almost 50% after installing the street light automation (SLA) system [34–36].

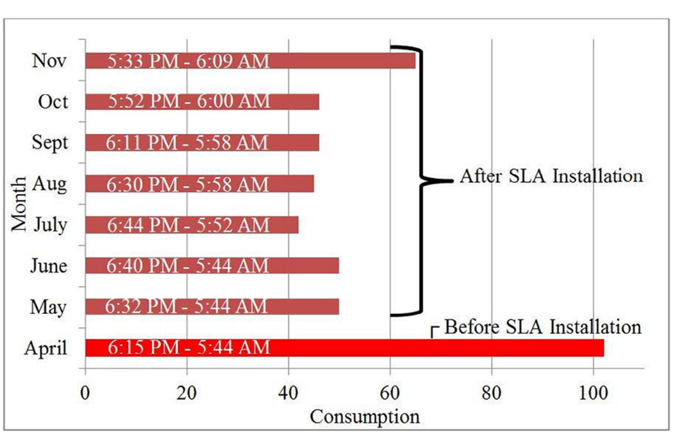


Fig. 18. Energy consumption before and after installation of SLA.

Table 7
Short list of few tampering and reported actions.

S. no.	Tamper detail	Action taken
1	Over current	Reported to PED, during inspection it was found that due to a function at consumer house and overdrawing sanction load. PED warned consumer to get separate permission for over drawl.
2	Over current	Reported to PED, during inspection it was found that meter reading more than actual consumption due to problem in the meter circuit and the same replaced with new meter.
3	Load through Earth	Reported to PED, during inspection it was found that there is a damaged wiring inside the house. Instructed to consumer to renovate the wiring.
4	Terminal cover open	Reported to PED, during inspection it was found that the consumer connected Welding machine. PED warned the consumer that he will be penalized if he repeats the same in future.
5	Terminal cover open	Reported to PED, during inspection it was found that the consumer shifted the meter location due to construction without the knowledge of PED staff
6	Terminal cover open	Reported to PED, during inspection it was found that the consumer shifted the meter location due to construction without the knowledge of PED Staff
7	Terminal cover open	Reported to PED, during inspection it was found that the consumer shifted the meter location due to construction without the knowledge of PED staff
8	Terminal cover open	Reported to PED, during inspection it was found that consumer bypassed the meter. PED warned the consumer that he will be penalized if repeats the same.

5. Payback analysis

After incorporating smartness in distribution network and analyzing its technical advantages the next step is to understand its contribution in economic terms. Increasing efficiency and savings of energy reflect in the economic benefits for both consumers and the utility. Advancements like ToU tariff and online real time monitoring of energy consumption allow the consumers to shift and schedule their load profile as per their convenience and consequently reduce electricity charges. Utilities also gain economic benefits through implementation of the smart grid technologies. Table 8 gives a detailed analysis of energy and cost saving of smart distribution network of Puducherry. Table 8 shows data of pre and post SG implementation with consequent economic gains. The total annual input energy for 4000 consumers is 172.08 MU. Out of this input energy, only 86% i.e. 157.99 MU was getting billed earlier and the rest 14% i.e. 24.09 MU was unbilled energy. It has been found that after installation of SG, the portion of billed and unbilled energy becomes 95.01% and 4.99% respectively, which is equivalent to 163.5 MU and 8.58 MU of energy. Considering $0.07 as an average per unit cost of input energy, the total cost of energy is $11,557,106.18. The total cost of billed energy at the rate of $0.07 per unit is found to be $9,939,266.53 before implementing SG technologies and it increases to $10,980,862.74 after implementing SG technologies. Billing efficiency (1) of utility has increased from 86% to 95.01%. Revenue collection efficiency has increased from 90.99% to 95.55%. Post-implementation revenue collection against billed energy reaches to $10,492,078.16 in respect of $9,043,783.33 of the pre-SG installed value. Unrealized revenue (2) has reduced to $488,784.58 from $895,483.20. AT&C losses (3) of utility have dropped to 9.21% after installing SG than its previous value of 21.75%. During the pre SG installed scenario, billing required a person going from door to door for collecting meter reading whose cost of $2.24 per consumer got reduced to $89,548.32 for 40,000 consumers. After implementing SG this manpower cost reduced to zero as SG eliminates need for door to door collection of meter data [37].

Table 8
Loss and benefit analysis in Puducherry smart grid pilot project.

Analysis component	Annual	
	Pre implementation	Post implementation
Input energy	172.08 MU	172.08 MU
Billed energy	147.99 MU	163.5 MU
Unbilled energy	24.09 MU	8.58 MU
Unbilled energy (%)	11.57%	5%
Per unit cost of input energy	$0.07	$0.07
Cost of input energy supply	$11,557,106.18	$11,557,106.18
Cost of billed energy	$9,939,266.53	$10,980,862.74
Billing efficiency	86.00%	95.01%
Collection efficiency	90.99%	95.55%
Revenue collection against billed energy (excluding arrears)	$9,043,783.33	$10,492,078.16
Uncollected revenue	$895,483.20	$488,784.58
AT&C losses	21.75%	9.21%
Cost of billing (per consumer)	$2.24	0
Cost of billing (40,000 consumers)	$89,548.32	0
Benefit due to billing efficiency		$1,041,596.21
Benefit due to collection efficiency		$68,653.71
Benefit from reduced cost of billing		$89,548.32
Thus estimated incremental revenue realization by implementing the SG		$1,199,798.24

$$\text{Billing efficiency} = (\text{billed energy}) / (\text{input energy}) * 100 \tag{1}$$

$$\text{Uncollected revenue} = \text{cost of billed energy-revenue collection against billed energy} \tag{2}$$

$$\text{AT\&C Losses} = 1 - (\text{billing efficiency} * \text{collection efficiency}) \tag{3}$$

$$\begin{pmatrix}\text{Benefit due to}\\ \text{billing efficiency}\end{pmatrix} = \begin{pmatrix}\text{cost of billed energy}\\ \text{after implementation}\end{pmatrix} - \begin{pmatrix}\text{cost of billed energy}\\ \text{before implementation}\end{pmatrix} \tag{4}$$

$$\begin{pmatrix}\text{Benefit due}\\ \text{to collection efficiency}\end{pmatrix} = (\text{difference of revenue collection}) * (\text{ratio of revenue collection}) \tag{5}$$

$$\begin{pmatrix}\textit{Difference of}\\ \textit{revenue collection}\end{pmatrix} = \begin{pmatrix}\textit{revenue collection}\\ \textit{against billed energy}\\ \textit{after implementation}\end{pmatrix} - \begin{pmatrix}\textit{revenue collection}\\ \textit{against billed energy}\\ \textit{before implementation}\end{pmatrix} \tag{6}$$

$$\text{Ratio of revenue collection} = \frac{(\text{revenue collection after implementation})}{(\text{revenue collection before implementation})} \tag{7}$$

Gain for the utility from the increase in billing efficiency is the difference of cost of billed energy, post and pre installation as in (4). Monetary gain due to increase in collection efficiency is a multiple of the difference and the ratios of revenue collection in pre and post SG installation are given in equations (5)–(7).

Thus as per Table 8, monetary gains after SG installation amounts to $1,199,798.24/year. It is important to notice that this benefit is due to:

a *Increased billing efficiency* (from 86% to 95%), achieved through reduction of distribution losses, contributes to an estimated additional revenue generation of $1,041,670.83 (15.51 MU × $0.07).

b *Enhancement in collection efficiency* from 90.99% to 95.55% attributes to the increase in collected amount by about $686,537.12. However here the benefit is estimated only interest foregone on the increased collected amount of $686,537.12, which is $68,653.71 at 10% interest per annum.

c *Reduced cost of billing* (saving due to reduction in cost of billing on account of doing away with manual meter reading) accounts to be $89,548.32 ($ 2.24 × 40,000).

Energy savings from peak load shaving, kVAr compensation though APFC, saving from automation of street lights etc. are not included. Adding economic equivalence of these additional savings would increase the SG benefit further. Proposed investment of $6,981,784.02 includes equipment cost, entry taxes, erection and F&I charges. Cost of equipment, entry charges and erection charges are one-time investment but F&I charges are to be distributed over entire period of the project life i.e. 15 years. Further this investment does not include operation and maintenance (O&M) cost which is to be distributed over the entire life span of the project. It is important to understand that the value of money changes with time and so the O&M cost and F&I charges that would occur in future do not hold the same value in the present. Present worth value (PWV) of future cost can be determined by multiplying the cost and the present worth factor (PWF). PWF can be obtained using eq. (8) [38,39].

$$PWF = \sum_{t-1}^{T} \left(\frac{1+IF}{1+IR} \right)^{t} \tag{8}$$

where IF stands for inflation rate and IR stands for interest rate.

With current inflation rate of 3.78%, interest rate of 12% and a project life span of 15 years, PWF is obtained as 0.58. The break up cost and their respective PWV are given in Table 9. Investment in equipment and software, entry charges and erection charges are to be a onetime investment at the beginning of the project and so PWF is not applicable to them. Charges on F&I and O&M are continuous investment and so their PWV is obtained by multiplying the cost with a PWF. Total cost of project including the operation and maintenance cost is $8,108,600.38 for which the present worth value is $7,493,701.91.

It is now seen that, of the total project investment of $7,493,701.91 made for the smart grid infrastructure the utility gets a benefit of $1,199,798.24 every year. Payback period is calculated by dividing the total investment by the benefit occurred and found to be about 6.25 years [40,41]. This shows that along with various technical and social gains, total investment in smart distribution network can be recovered in just 6.25 years, after which utility can utilize the benefit occurred for other network advancements.

Table 9
Project cost and respective present worth value.

S. no	Particulars	Cost	PWV
One time investment:			
1	Equipment and software	$5,631,096.86	$5,631,096.86
2	Entry fee at 8%	$450,726.54	$450,726.54
3	Erection charges at 10%	$562,661.94	$562,661.94
Continuous investment:			
4	F&I taxes at 6%	$337,298.67	$195,513.83
5	O&M at 20%	$1,126,816.36	$653,702.74
	Total	$8,108,600.38	$7,493,701.91

6. Sensitivity analysis

The uncertainties in the calculation of RoI and Payback periods of SG implementation mainly depend on two major factors viz. Utility tariffs and SG project costs:

a *Utility tariff impact*: In the event of an increase in PED's power purchase cost, the future increment in the demand can be met through power saved in the form of reduced AT&C losses or the demand side management measures like demand response resulting out of the installation of SG infrastructure. Further, an increase in the consumer tariffs in the future will also force the consumers toward optimizing their consumption and encourage to export more power to the grid through their roof top solar. These futuristic impacts are the uncertainties that will alter the pay-back period.

b *SG project cost*: The other uncertainty to consider is the scaling up of SG projects from the pilot stage. When smart grid is deployed on a larger scale, due to the increase in purchase SG infrastructure products such as Smart meters, the individual per unit component cost tends to reduce and may result in lesser cost for the SG implementation which would also effectively reduce the RoI and payback periods.

In future, with the advent of more advanced as well as cost-effective smart grid technologies toward development of photo voltaic panels, smart meters, outage management equipment, distribution system health monitoring systems and improved metering infrastructures (AMI), the impact of smart grid on the existing system will be much more significant. The cost and technical impact of these improved SG components will result in certain impact on the results of techno economic analysis and payback analysis. With such technological advances in SG infrastructure, the payback period is expected to reduce as more accurate metering by Puducherry Electricity Department (PED) will improve billing efficiency and AT&C losses which further increase the return on investment (RoI) through effectiveness of the smart-grid implemented in Puducherry. On the contrary, one of the important factors which may pull back the efficiency of the implemented smart-grid in Puducherry is the climatic/environmental condition. Since Puducherry is a coastal city, the saline pollution and salty wind may accelerate the rusting of SG infrastructure, panels, structures, frames and PV-panels which will deteriorate the efficiency nonlinearly that may add up to the deviations in the expected results. The study of these issues and challenges can be taken up in the future work.

7. Conclusion

Incorporation of Smart Grid technologies has resulted in tremendous peak shaving (up to 66% shaving). Further 25% of the conventional energy meters that were either stuck or faulty has been replaced with smart meters which resulted in a 20% increase of revenue for the utility. Analysis shows that a utility could achieve an average of 34.66% energy saving on selected SP Nagar DT level through peak load shaving. APFC and active filter have improved the power quality of distribution network. DTMS and FPIs are found to be monitoring the network in an efficient manner which led to lesser interruptions, quick detection of fault and fast recovery of supply. It is interesting to notice that energy saving could be achieved through street lights automation too.

Capital investment of Puducherry smart grid pilot project is $6,981,784.02 for 40,000 consumers. Addition of operation and maintenance cost (as 20% of equipment and software cost) makes the total investment equal to $8,108,600.38, which present worth value is $7,493,701.91. It has been shown in this study that this investment can be recovered in 6.25 years through benefits from increase in billing efficiency, collection efficiency and reduced cost of billing only. This analysis also brings out that, smart distribution network is feasible techno-economically and certainly the best choice for all stakeholders. This article also establishes that SG installations result in a profit to the consumers in the form of increased reliability, quality, and satisfaction and reduced energy charges. From utility's perspective, SG enhances the revenue along with superior capabilities at every aspect of distribution network and system operation. Outcome of this analysis therefore encourages deployment of smart distribution network across the country.

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