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Communication Modeling of Solar Home System and Smart Meter in Smart Grids

S. M. SUHAIL HUSSAIN[1], (Student Member, IEEE), ASHOK TAK[2], TAHA SELIM USTUN[3], (Member, IEEE), AND IKBAL ALI[1], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Jamia Millia Islamia, New Delhi 110025, India
[2]Load Dispatch Center, Electrical T&D, Tata Steel Ltd., Mumbai 400001, India
[3]Fukushima Renewable Energy Institute, AIST, Koriyama 963-0298, Japan

Corresponding author: S. M. Suhail Hussain (suhail@ieee.org)

ABSTRACT The future energy networks are envisioned to be green and clean with high penetration of renewable energy-based generators. The most promising type is solar energy which has immense potential around the globe. Solar home systems (SHSs) with rooftop solar panels are proliferating in urban cities as well as in distant rural areas. Possible interaction of SHS with utility grid will result in dynamic power flow which is a huge challenge for power utility authorities and consumers. The smart meters (SMs) are being deployed to make this possible through bi-directional energy and information exchange. In order to address this need, this paper develops the communication models of SHS and SM based on the IEC 61850 standard. These models provide standardized approach to these technologies and facilitate a series of functionalities, such as power flow control, demand response, and other ancillary services, using configured message exchange. The detailed models, their use cases and the messages are studied in detail. Furthermore, extensive simulations are run with riverbed modeler to investigate the dynamic performance. IEC 61850-based models of SHS and SM are implemented, message frames are developed according to use cases, and the functionalities mentioned earlier are run as scenarios. Finally, the performances of different communication technologies have been analyzed to estimate their adequacy for smart grid implementations.

INDEX TERMS Solar home system, smart meter, IEC 61850, communication infrastructure, smart pricing.

I. INTRODUCTION

The electric networks are now transforming towards a clean power grid as more renewable energy resources are integrated. The integration of these distributed energy resources (DERs) is challenging, considering the centralized nature of conventional grid and lack of reliability due to their intermittency [1]. These DERs can be Photo Voltaic (PV) systems, wind generators or Solar Home Systems (SHS) in rural microgrids or urban residences.

SHS is a small energy system including local rooftop PV generation with energy storage systems and loads [2]. This concept is becoming popular with high deployment of PV panels to residences with purpose of having clean, green and independent energy supply [3]. When connected to the utility grid, SHS may have bi-directional power flow to supply or sink energy to/from the grid. Various novel challenges are introduced by this behavior and they can be mitigated with the implementation of effective communication and coordination [4].

Smart Meters (SMs) are used to monitor flow of energy between a household and the utility grid. Their deployment is a step towards Automatic Metering Infrastructure (AMI). High SM proliferation is an essential step for achieving adequate communication in smart grids and can be leveraged to mitigate challenges such as power flow and protection [5].

Considering the number of SMs and SHSs that may be deployed in a grid and the possibility of them being from different vendors, it is clear that a common language has to be established for seamless and interoperable operation [6]. To facilitate standard communication in the power networks, various approaches have been developed [7], [8]. However, most of these approaches present challenges of feasibility, flexibility and interoperability. The most popular standard with Object-Oriented and interoperability design is IEC 61850 which is being deployed widely in the power utility automation communication networks [9]. For communication utilization in microgrids, IEC Working Group (WG 17) published extension part IEC 61850-7-420, which is very inclusive for integrating DERs into communication infrastructure of power systems [10]. Different DERs and controllable loads have been modeled with logical devices and logical nodes (LN) of IEC 61850 standards in [11]–[14].

IEC 61850 communication models have been developed for multi-level management [15], energy management automation [12], Volt-VAR optimization [16] and hybrid agent architecture for automation [17] of microgrids/smart grids. IEC 61850 based PMU communication models for wide area communication have also been studied in [18], [19]. Recently, IEC 61850 based communication models for DSTATCOM has been reported in [20]. Previous work in [21] and [22] addresses the modeling of Electric Vehicles (EVs) with IEC 61850 and development of system architecture, data set design and communication for implementation of V2G system with IEC 61850. As it can be seen, IEC 61850 is emerging as one of the most promising solutions for communication standardization in power utility automation domain.

However, until now, the IEC 61850 standard does not cover all entities that may be present in a smart grid such as SHS and SM. Feuerhahn *et al.* [23] reported that IEC 61850 based MMS protocols are most suitable for SM communication networks. However, there is little work on SHS and SM communication modeling according IEC 61850 in literature. Liu *et al.* [24] and Vyatkin *et al.* [25] have proposed some preliminary models for SM, yet these models do not take smart pricing into effect and are inadequate for full smart grid implementation.

In order to address this knowledge gap, this paper presents IEC 61850 based modeling of SHS and SM to facilitate their integration to power systems and to ensure interoperability among different devices. In this fashion, a more holistic modeling can be achieved and different components that may be present in a grid can communicate in a standard manner. Since this removes the barrier of integrating equipment from different manufacturers, it is a solid step towards plug-and-play (PnP) in smart grids. Furthermore, the performance of the proposed SHS communication model is evaluated for different communication technologies in terms of End to End (ETE) delay for different messages exchanged.

The rest of the paper is organized as follows: Section II introduces the SHS operation and related use cases in smart grids. Section III details the developed IEC 61850 based models of SHS and SM. Section IV presents different functionalities using the developed models. Section V shows the message modeling, simulations and discussions on performance/validation using Riverbed Modeler tool [26]. Finally, Section VI presents the conclusions.

II. SHS OPERATION AND ITS USE CASES IN SMART GRIDS

SHSs are emerging in urban cities as well as in remote rural areas. With the focus on extracting solar energy, installation of rooftop PV panels is trending around the globe [27]–[29]. A SHS consists of PV panels as generation, batteries as storage devices, and local appliances including mobile charging, lightning bulbs and telecommunication devices as loads. PV panels are connected to power infrastructure through inverter which acts as node for SM to grid, residential loads and storage devices as shown in Fig. 1. The SHS can operate in stand-alone as well as grid connected mode depending upon availability of local generation and the electricity price.

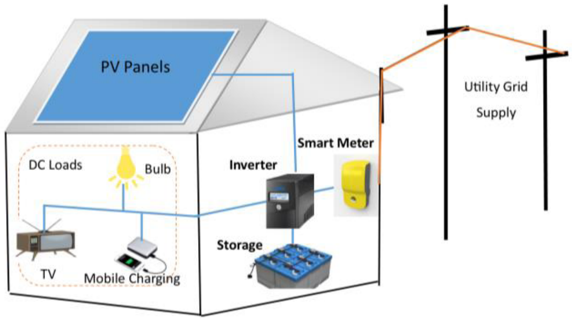

FIGURE 1. Block Diagram of SHS.

Smart grids utilizes Information and Communication Technologies (ICT) to monitor and control power flows with an objective to make the power grid more resilient, efficient and cost effective. The SHSs in smart grid may contribute in intelligent load shedding processes, Volt/VAR control or demand response which can help in achieving the objectives of smart grid. Distribution System Operator (DSO) generates the schedules and control signals for all the DER systems in the distribution system. However, small DER systems (such as SHS) cannot directly exchange the energy with the grid and participate in electricity markets. Hence, the figure of the aggregator is introduced, which is widely accepted for enabling the participation of DERs in the grid energy exchanges and electricity markets. SHS can participate in grid energy exchanges by being the part of the aggregations. This can be in three ways:

1. SHS can be part of the virtual power plants (VPP) dispatched by DSO.
2. SHS can participate in demand response methods (curtailing loads)
3. SHS via aggregators can participate in providing ancillary services.

A. SHS AS ENERGY RESOURCE

Based on the energy consumption pattern and energy generation profile, the SHS owner registers the technical capabilities of SHS system, such as power rating and location, with the aggregator. The aggregator filters and selects the SHS out of the pool that can serve the demand of the DSO. These clustered SHS are offered as VPPs.

B. SHS FOR DEMAND RESPONSE

SHS can participate in demand response either individually or via an aggregator as per the regulator or utility policies. In case the dynamic prices are made available at household level; when the energy price is high, SHS may reduce the load consumption by taking off the non-critical load or shift the load to other time periods when the price of energy is low.

Sometimes, based on prognosis from grid topology, demand history, forecasted demand and grid capacity,

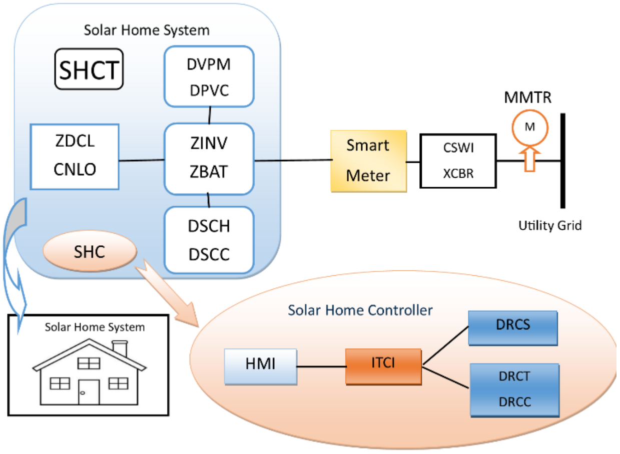

FIGURE 2. SHS Modeling with IEC 61850.

the DSO identifies the areas where congestion or power shortage or Volt/VAR fluctuations are likely to occur. DSO will, then, issue a request for providing the energy to be diverted to the concerned aggregators. In such cases, SHS may bid with their aggregators to curtail a certain amount of load. The aggregator clusters the load reduction bids of SHS and other DER service bids, if any, and negotiates with DSO. For such cases, the SHS systems must be ready to curtail their loads on a short notice period.

C. SHS PARTICIPATING IN ANCILLARY SERVICES

Aggregators coordinate SHS to provide ancillary services such as frequency support or energy balancing in real-time. To participate in ancillary services, SHS must register their power capacity within which they can be dispatched in real-time to the aggregators. Depending upon the ancillary service market rules, capacities may be required an hour to a week ahead of the delivery of services. Whenever there is request for ancillary services from DSO, aggregators bid to provide these services. In turn, the aggregator's issues ancillary services profiles to all the SHS systems that has committed to provide the ancillary services.

III. MODELING SHS AND SM WITH IEC 61850-7-420 FOR SMART GRID COMMUNICATION INFRASTRUCTURE

A. SHS MODELING

Interaction of utility grid and SHS poses challenges for efficient and automated interaction. Hence, communication infrastructure for SHS has to be designed for its integration in power grid with dynamic power flows. The consumer end behavior, demand side management and power supply economics can be enhanced significantly by applying communication configuration of SHS.

TABLE 1. Description of SHCT Logical Node.

SHCT Class			
Data Name	**CDC**	**Explanation**	**M/O/C**
LNName		Shall be inherited from logical-node class (see IEC 61850-7-2)	
		Settings	
SH2GStart	ASG	SH2G-Allowed Connection Start Time	O
SH2GEnd	ASG	SH2G-Allowed Connection End Time	O
G2SHStart	ASG	G2SH-Allowed Connection Start Time	O
G2SHEnd	ASG	G2SH-Allowed Connection End Time	O
SHReady	ASG	Time when SHS storage and generations are ready to deliver power	O
GridReady	ASG	Time when Grid is ready to receive power from SHS	O
IAlim	ASG	Input Current Limit	O
OAlim	ASG	Output Current Limit	O
IVlim	ASG	Input voltage limit	O
OVlim	ASG	Output voltage limit	O
SH2GMode	ING	Types of connection modes 1 = As Energy Resource 2 = Demand Response 3 = Ancillary Service	M
		Status Information	
ConnCount	INS	Count of grid connection	M
SH2GStatus	SPS	True: SH2G scheme is ON False: SH2G scheme is OFF	M
G2SHStatus	SPS	True: G2SH scheme is ON False: G2SH scheme is OFF	M
EconStatus	SPS	True: Economic Connection is selected False: Immediate connection is selected	M
ConnectSign	SPS	True: Grid Connection Signal is ON False: Grid Connection Signal is OFF	O
StorFullSign	SPS	True: Storage devices full Signal is ON False: Storage devices full Signal is OFF	O
		Controls	
SH2GEnable	DPC	Grid Connected or Islanded Operation GridConnected=True, Island=False	M
SH2GSwitch	DPC	Switch SH2G or G2SH connection SH2G=True, G2SH=False	M
EconConnect	DPC	Switch economic and immediate connection, Economic=True, Immediate=False	M
		Measured Values	
DelPower	MV	Power delivered to grid by SH2G scheme	O
RecPower	MV	The amount of power received by SHS	O
SHPrice	MV	The current SHS price for energy delivery	O
GridPrice	MV	The current grid price for energy supply	O

IEC 61850-7-420 standard contains the LNs for different DER systems communication modeling. However, it does not cover system-view and specifications about various DER components and their interaction with grid with specified functions in application view [8]. Same standard, i.e. IEC 61850-7-420, is used for modeling all components of SHS such as PV generations, storage batteries and loads. Fig. 2 shows the overview of all LNs associated with SHS.

Making use of already developed LNs in IEC 61850-7-420, PV System, Solar Home Controller, circuit breaker and measurement devices have been modeled. It is contribution of this manuscript to combine these LNs towards modeling an SHS. The novel modeling for representing SHS functionalities as discussed above is done by developing a new logical node class, SHCT, as shown in Table 1 and discussed below.

PV system is modeled with DVPM and DPVC LNs [12]. The interconnecting inverter/rectifier is modeled by ZINV/ZRCT LNs respectively. Through the DCCT the SHS registers its technical capabilities to the aggregator. The DSCH receives the energy service schedules for SHS from the aggregator. DSCC is used to control or set the energy or ancillary service schedule in the SHS. The DC loads are modeled by ZDCL, whereas the controllable loads are modeled by CNLO [12]. The storage device and its controller in SHS are represented by LNs ZBAT and ZBCT. SHS is connected to grid via a switch and circuit breaker, modeled by CSWI and XCBR LNs. The SHC block in SHS is SHS controller to be used for controlling various LNs to make suitable decision by user or utility grid.

SHC is a group of LNs which are used for interaction of user and utility to control the bi-direction power flow and economic schemes for energy consumption and generation. The LNs in SHC are IHMI for SHS user interface and ITCI for control and communication interface which is connected to DRCS and DRCT corresponding to DER controller status i.e. PV panel status and its controller respectively.

The newly developed SHCT LN includes all the necessary parameters to control SHS's operation and functionalities. The SHS to Grid or Grid to SHS connection time is monitored by Data Objects (DOs) '*SH2GStart*', '*SH2GEnd*', '*G2SHStart*' and '*G2SHEnd*' of SHCT. '*SHReady*' DO denotes the time interval when SHS is ready to deliver power into grid. Similarly, '*GridReady*' is time duration when grid is ready for injection of power from remote distributed resources.

'*IAlim*' and '*IVlim*' are parameters for input current and voltage limits, respectively, whereas '*OAlim*' and '*OVlim*' are for output current and voltage limits for SH2G operation, respectively. '*ConnCount*' tracks the number of times grid connected for recording history of stand-alone or grid connected operations. '*SH2GStatus*' is set to "True" if power is delivered from SHS to grid and '*G2SHStatus*' is set to "True" otherwise. '*EconStatus*' presents whether SHS is connected to grid for economic power transfer during non-peak and peak times. '*SH2GEnable*' is set to "True" if SHS is connected to grid and "False" if it is operating in islanded mode, while '*SH2GSwitch*' changes its operation from power sourcing ("True") to power sinking ("False"). The switching of different operation can be done by SHS user or, in case of demand side management, by the utility grid using communication configuration. The interaction of SHS with the grid depends on the status of the latter. Hence, SHS interacts with the grid using bi-lateral agreement. Fig. 3 shows virtualization of SHS and SH2G technology by IEC 61850-7-420 based modeling.

The measured values section has items of delivered ('*DelPower*') and received power ('*RecPower*') as well as pricing for energy generated by SHS ('*SHPrice*') and energy purchased from the grid ('*GridPrice*'). These measured values play an important role in power flow control and smart pricing for realization of smart grid at house hold level. SMs are used for this purpose to perform smart economics and they should also be modeled in a standard fashion.

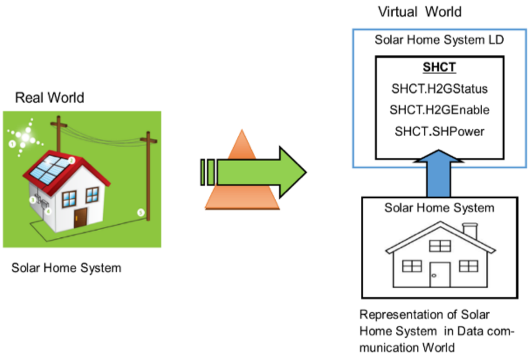

FIGURE 3. Virtualization of SHS with proposed LNs.

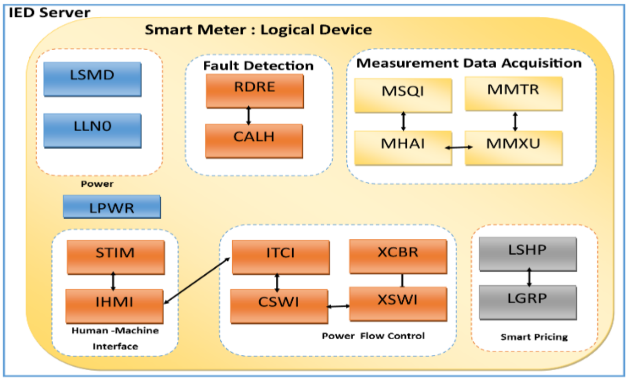

FIGURE 4. SM Modeling with IEC 61850.

B. SM MODELLING

SMs play a vital role in smart grid operation with multiple operations they perform, including energy pricing. These are considered to be the back-bone of distribution systems in future power grids. With the proliferation of local generation, e.g. PV panels, SMs need to deal with bi-directional power flow and they need to be controlled by user and utility through communication system. In order to facilitate their integration into power systems, SMs should also have a standard modeling based on IEC 61850. To that end, preliminary models of LN classes for specific functions of SM were developed in [24]. The detailed communication modeling of SM using IEC 61850 standard is presented as shown in Fig. 4.

The SM contains several LNs corresponding to different functions. The functions of SMs includes power flow control, measurement data acquisition and its processing, fault detection and protection, human–machine interface (HMI) and smart pricing.

The power flow control section is responsible for tracking dynamic power flow using controller interface (ITCI) connected to SHS user (IHMI). The SHS can be switched between grid connected to stand-alone mode using switch controller (CSWI), physical switch (XSWI) and tripping circuit breaker (XCBR). Measurement and data acquisition section uses MMXU and MMTR LNs to measure voltages, currents, powers and energy. Other specific LNs include MSQI for sequence and inter-harmonics measurement and MHAI for harmonics and inter-harmonics measurement. The protection and fault detection is done with help of RDER

TABLE 2. Description OF LGRP logical node.

LGRP Class			
Attribute Name	***Attribute Type***	***Explanation***	***M/O***
LNName		Shall be inherited from Logical-Node Class (See IEC 61850-7-2)	
Data			
Measured Values			
StoredPrice	CUG	Grid Stored Price	M
CurrentPrice	CUG	Grid Current Price	M
Setting			
GRTime	ORG	Provides Sampling Time for Grid	O
WinTms	ENG	Time Window (in seconds) within which current pricing signal must be applied.	O
CrntTms	ENG	Timeout period for current pricing signal	O

TABLE 3. Description of LSHP logical node.

LSHP Class			
Attribute Name	***Attribute Type***	***Explanation***	***M/O***
LNName		Shall be inherited from Logical-Node Class (See IEC 61850-7-2)	
Data			
Measured Values			
StoredPrice	CUG	Solar Home System Stored Price	M
CurrentPrice	CUG	Solar Home System Current Price	M
Setting			
WinTms	ENG	Time Window (in seconds) within which current pricing signal must be applied.	O
CrntTms	ENG	Timeout period for current pricing signal	O

LN, used for disturbance recording and processing. If any ambiguity detected, then alarm handling controller (CALH) warns the system to switch operation. For smart pricing functionality between SHS and utility grid, two new LNs LGRP and LSHP are developed in this paper, which are shown in Table 2 and Table 3, respectively.

The newly developed LGRP LSHP LNs contains the DOs for the stored and current prices of utility grid and SHSs in the *'StoredPrice'* and *'CurrentPrice'*, respectively. The time period within which the current pricing signal must be applied is denoted by DO *'WinTms'*, while the DO *'CrntTms'* denotes the timeout period of current pricing signal.

IV. PROPOSED FUNCTIONALITIES FOR SHS AND SM

Based on SHS, SM models and operation case scenarios developed in previous sections, the communication mapping is presented in this section.

A. SHS as Energy Resource

Bi-directional power flow between SHS and grid can be controlled by the house owner and grid via communication infrastructure. The modelled SHCT LN plays an important role in power flow control case using section data parameters i.e. settings, status information of SHS and control methods. The bi-directional power flow is controlled by parameters in controls section of SHCT LN.

There are two possible operating modes, i.e. islanded mode and grid connected mode, and these modes are dependent upon local generation value. There are three possible cases, considering local generations: (1) Sufficient generation only for SHS, (2) Generation scarcity and (3) Over-generation to be fed to grid.

If SHS has sufficient local generation, it will operate in islanded mode with *'SH2GEnable'* = *False* and status information as *'SH2GStatus'* = *False* as well as *'G2SHStatus'* = *False*. While in islanded mode, SHS simply acts as isolated microgrid with no exchange with power grid and local generation is used for storage and local loads.

However, if SHS needs to import power from the grid, the status of grid is checked by *'GridReady'* and if *'GridReady'* = *1*, then the control parameter *G2SHEnable* is toggled to "True". The connection nature is determined either economic or immediate connection. Hence, *'G2SHStatus'* = *True*, *'SH2GStatus'* = *False* and timer starts with connection i.e. *'G2SHStart'* = *1* for allowed time for particular connection. Also, *'ConnCount'* is incremented with each new connection. The power received from grid is measured using parameter '*RecPower*'. *'SH2GEnd'* is enabled after allowed time ends. And connection is ended with *'SH2GStatus'* = *False*.

When SHS has more generation, this can be exported to the grid. Normally, the SHS owner registers the technical capabilities of the SHS with the aggregator. This is done by sending the information in DCCT LN of SHS to aggregator. The aggregator forms a VPP with the clusters of SHS and other DERs, and presents it for economic dispatch. The aggregator receives the energy dispatch schedule from the DSO, in turn the aggregator sends the energy dispatch schedules to the all components of VPP. The SHS receives the energy schedules from aggregator in the DO '*SchdTyp*' of LN DSCH. And the schedule is set in SHS by enabling the DO '*ActWSchd*' to "True" in DSCC LN. Next, if *'SHReady'* = *True* and *'SH2GStatus'* = *False*, SHS is connected to grid with *'SH2GEnable'* = *True* and *'SH2GSwitch'* = *True*. The *'SH2GStart'* is set "True" for allowed time.

The output current and voltage limits (*'OAlim'*, *'OVlim'*) are checked before supplying power. The output delivered power (*'DelPower'*) is measured for duration between *'SH2GStart'* = *True* and *'SH2GEnd'* = *True*. When *'SH2GEnd'* = *True*, the connection is ended using SHC and power flow control section of SM.

Data messages mapping for power flow control is as follows:

Consider a SHS with a SM installed for communication and pricing of bi-directional power flow. The operation of SHS for different scenarios, explained above, is used for mapping the data messages used in SHCT LN and SM model. Power flow control functionalities uses specific LNs block of

SM model and parameters of status information & control sections of SHCT LN.

In an SHS, the bi-directional power can flow through SM. Incoming power from grid to SHS (Pgrid) and available power which can be sent to grid (Pshs) can be tracked by LNs and its parameters. If SHS operator wants to check the various power values, it can be controlled using settings as follows

$$\begin{aligned} \text{Pgrid} &= \text{MCPU} \rightarrow \text{SHS1.IHMI} \\ &\rightarrow \text{SHCT.(OAlim}^{*}\text{OVlim)} \\ \text{Pgen} &= \text{MCPU} \rightarrow \text{SHS1.IHMI} \rightarrow \text{SHS1.ITCI} \\ &\rightarrow \text{SHS1.DRCS} => \text{SHS1.DVPM} \\ \text{Pload} &= \text{MCPU} \rightarrow \text{SHS1.IHMI} \rightarrow \text{SHS1.ITCI} \\ &\rightarrow \text{SHS1.DRCS} \rightarrow \text{SHS1.CNLO} \\ \text{Pstore} &= \text{MCPU} \rightarrow \text{SHS1.IHMI} \rightarrow \text{SHS1.ITCI} \\ &\rightarrow \text{SHS1.DRCS} \rightarrow \text{SHS1.ZBAT} \end{aligned}$$

The available power which can be feed to grid is,

$$\text{Pshs} = \text{Pgen} - \text{PLoad} + \text{Pstore}$$

The SH2G operation includes enabling and disabling the grid connection using control parameters such as:

(a) For Enabling SH2G:

There would be excess power with SHS which is to be fed to grid, therefore, Pshs is positive & *'SHReady'* = "True". If SHCT.SH2GStatus = "False", then

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GEnable} = \text{True)}$$

And if SHCT.G2SHStatus = "True",

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GSwitch} = \text{True)}$$

And the *'SH2GMode'* is set to 1 (i.e. energy resource)

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GMode} = 1)$$

The energy service schedule received from the aggregator is set by the following mapping:

$$\begin{aligned} \text{Aggregator} &\rightarrow \text{SHS.IHMI} \rightarrow \text{DSCH.(SchdTyp} = 1) \\ \text{MCPU} &\rightarrow \text{SHS.IHMI} \rightarrow \text{DSCC.(ActWSchd} = \text{True)} \end{aligned}$$

(b) For Disabling SH2G :

SHS would be in need of grid power, and accepts the grid power (Pgrid).

If SHCT.SH2GStatus = "True", then

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GEnable} = \text{False)}$$

And if SHCT.G2SHStatus = "False", then,

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GEnable} = \text{False)}$$

And, power transfers are measured with MMXU node in SM using settings time parameters i.e. *'SH2GStart'*, when SH is connected to grid; *'SH2GEnd'*, when SH is removed from grid; similar for *'G2SH'* operation etc.

B. DEMAND RESPONSE THROUGH SHS AND SM

The aggregator or utility, through Utility Control Desk (UCD), notifies the dynamic energy price of the grid to the SHS owners via the SM LN LGRP. The *'CurrentPrice'* DO contains the dynamic grid price. When the grid price is at higher side, the SHS controller can reduce the load by controlling the direct controllable loads (DCL). DCL (e.g. air conditioners, thermostats etc.) can be operated at less than rated capacity during emergency or peak load conditions. The operating mode of DCL can be set by issuing a setting command at DO '*DCLMode*' in the CNLO LN of controllable loads.

The setting for implementing the demand response is performed as follows:

Initially the SHS is set to the demand response mode by setting *'SH2GMode'* to 2 as follows,

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GMode} = 2)$$

The current price of grid is taken in SHS1 as follows,

$$\begin{aligned} \text{MCPU} &\rightarrow \text{SHS1.DMSC} \rightarrow \text{SHS1.SM1.LGRP} \\ &\rightarrow \text{SHS1.SM1.LGRP.CurrentPrice} \end{aligned}$$

If the current price is more than the threshold, the DCLs are issued command to reduce their power consumption by setting the mode of DCL as follows:

$$\begin{aligned} \text{MCPU} &\rightarrow \text{SHS1.CNLO} \rightarrow \text{SHS1.CNLO1.DCLMode} \\ &\rightarrow \text{SHS1.CNLO1.DCLMode.}(0, 1, 2, 3) \end{aligned}$$

C. ANCILLARY SERVICES THROUGH SHS AND SM

Based on the expected energy production and consumption, every SHS registers its power capacity within which it can be dispatched in real-time. When there is a need for ancillary services in the grid, the aggregators coordinate SHSs to provide ancillary services in real-time. The aggregators send the ancillary services profiles such as contingency reserve "spinning", contingency reserve supplemental, emergency reserve, energy balancing, reactive power support, emergency islanding to the SHS controller. These profiles are set in the '*SchdTyp*' of LN DSCH of the SHS controller. The communication mappings for setting the ancillary services are as follows:

Initially the SHS is set into the ancillary services mode by setting *'SH2GMode'* to 3 as follows,

$$\text{MCPU} \rightarrow \text{SHS.IHMI} \rightarrow \text{SHCT.(SH2GMode} = 3)$$

The energy service schedule received from the aggregator is set by the following mapping:

$$\begin{aligned} \text{Aggregator} &\rightarrow \text{SHS.IHMI} \rightarrow \text{DSCH.(SchdTyp} = x) \\ \text{MCPU} &\rightarrow \text{SHS.IHMI} \rightarrow \text{DSCC.(ActWSchd} = \text{True)} \end{aligned}$$

V. SIMULATION OF PROPOSED COMMUNICATION INFRASTRUCTURE IN SHS NETWORKS

Using new IEC 61850 based communication models of SHS and SMs, different wired and wireless communication technologies are simulated using Riverbed Modeler. Different

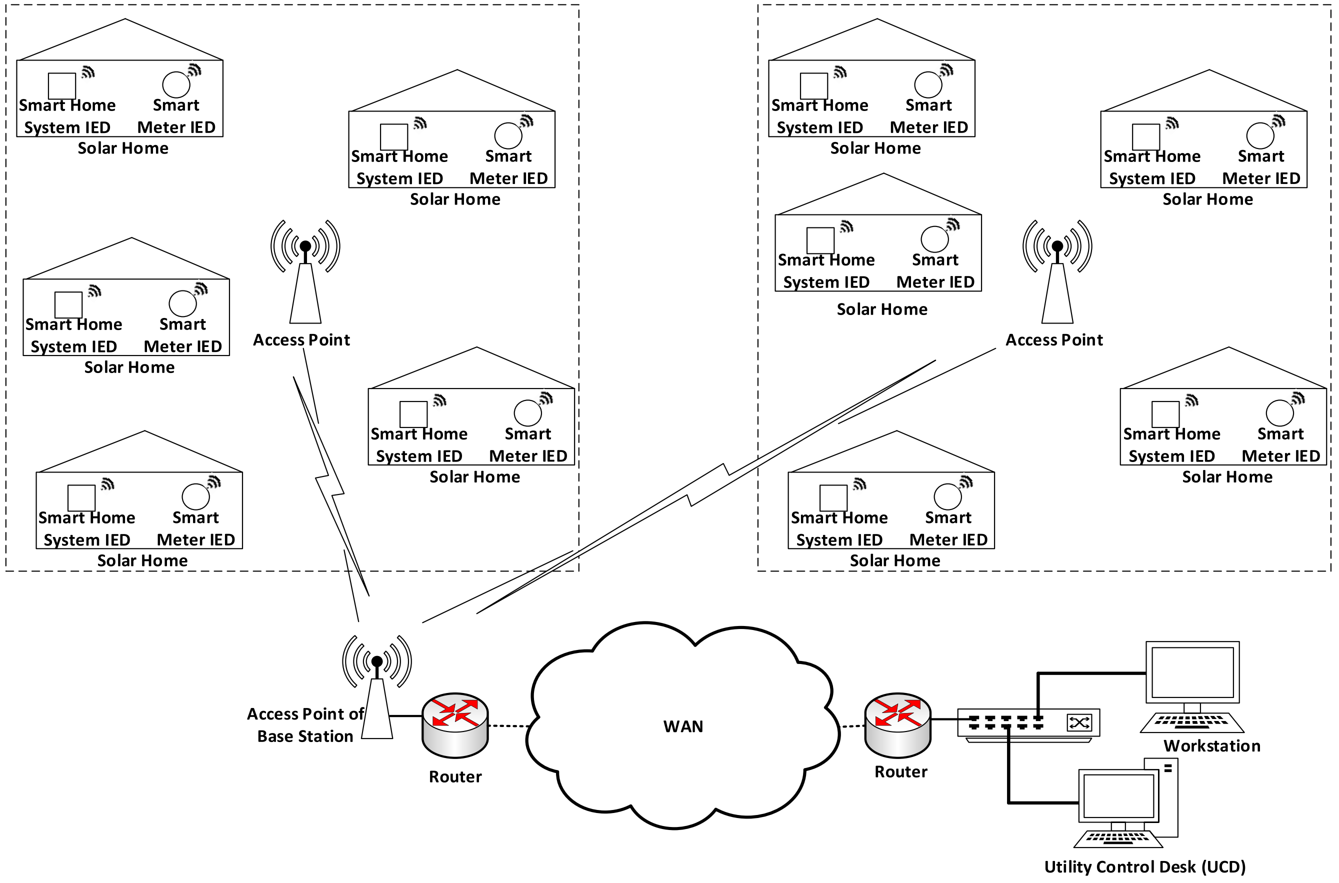

FIGURE 5. Communication Network Architecture of Ad-hoc SHS microgrid.

sizes of ad-hoc SHS microgrids (such as 20 SHS, 50 SHS and 100 SHS based microgrids) are modeled and ETE delay performance of different messages are investigated for different communication technologies such as LAN, WiFi (IEEE 802.11n/g) and WiMAX. Figure 5 shows the communication network architecture of the ad-hoc SHS microgrid. Each solar home consists of SHS IED and SM IED. 5 SHSs are grouped as a cluster. All the SHS and SM IEDs in a cluster are connected to a receiver (access point) in WiFi/WiMAX networks (or to a common switch in Ethernet based LAN networks). The cluster access points are connected to base station access point as shown in Fig. 5. The base station access point further connects to the UCD via a wide area network, since the SHS ad-hoc microgrids and UCD can be geographically distantly located. The messages exchanged between SMs, SHSs and the UCD are in form of IEC 61850 based GOOSE, Sample Value (SV) and status update messages.

A. TRAFFIC MODELING BETWEEN DIFFERENT IEDs

The description of different messages communicated among various SHSs, for use cases discussed in section IV is given in Table 4. As seen, their Application Protocol Data Unit (APDU) sizes, destination and source IEDs are also given.

TABLE 4. Messages exchanged between SHS IEDs.

Type of message	Type/ format	Source	Destination	Size of APDU (bytes)	Sampling Rate (/s)
Measured data	Sample value	SM IED	SHS IED,	96	4000
Status Updates	MMS – Client sever	SM IED	Aggregator, SHS IED	100	10
		SHS IED	Aggregator	395	10
		SHS, UCD	UCD, SHS	200	Event Based
Trip Command	GOOSE	SHS IED	SM IED	104	Event based
Pricing data	MMS – Client sever	SM IED	UCD	158	0.2
		UCD	SM IED	158	0.2

The measured data is cyclic in nature, i.e. each SM samples the values of voltage and current at 4000/4800 (for 50/60 Hz) samples per second. Status update messages can be classified as 2 types, i.e. the periodic updates and event based updates. Each SHS and SM regularly reports its status to the aggregator every 0.1 second in the form of periodic status updates. In wake of any event, status update messages are exchanged between SHSs and aggregators which are event based status update messages. The events may occur at any time, therefore, the traffic of event based updates are modeled with suitable stochastic processes. Hence the event based status update messages are modeled with negative exponential distribution function given by

$$F(t) = \lambda e^{-\lambda t}, \quad t > 0 \tag{1}$$

where $(1/\lambda)$ is the average time interval between the two consecutive packets. The value of λ is set to 10. Similarly the GOOSE messages are also event triggered and bursty in nature, therefore, these messages are also modeled with Weibull distribution function. The burst data of GOOSE messages is transmitted for a short period of time. Weibull distribution function is suitable to represent the nature of GOOSE messages as it is a heavy tailed function normally used to model fixed rate in ON period and ON/OFF period lengths, when producing self-similar traffic. The Weibull distribution function is given as

$$F(t) = 1 - e^{-\left\{\frac{t}{\beta}\right\}^{\alpha}}, \quad t > 0 \tag{2}$$

For simulation, the values of β and α are considered as 0.1 and 0.9, respectively. It is assumed that the UCD sends the pricing signals to the SMs for every 5 seconds.

B. MESSAGE FORMATS AND SIZES

The size of different messages exchanged is calculated by adding suitable protocol overheads and data payload to each message. The standard Ethernet frame has a protocol overhead of 24 bytes (7 preamble, 1 SFD, 6 destination address, 6 source address, 2 type, 4 CRC), whereas the WiFi (IEEE 802.11) and WiMAX (IEEE 802.16) have protocol overheads of 34 bytes and 9 bytes, respectively. The size and details of different fields of GOOSE, SV, status update and pricing signal APDUs are given in Fig. 6. SV and GOOSE messages are mapped directly onto Ethernet layer hence do not contain TCP/IP layers, while MMS type messages have TCP, IP headers.

The size of data present in each message is calculated by adding the sizes of required data objects of LNs for a particular application. The data (in IEC 61850) is normally in TLV (tag, length, value) ASN.1 BER type format. The size of "value" field for different data objects is either boolean (1 byte), INT32 (4 bytes) or string (8 bytes).

C. SIMULATION RESULTS AND INFERENCES

The proposed SHS based microgrids of different sizes are simulated in Riverbed Modeler to investigate the communication infrastructure performance. In order to evaluate the effectiveness of the proposed communication, the ETE delay performance and packet loss under different background traffic are studied. The ETE delay is the time required to send a packet from the source IED to the destination IED. The ETE delay is sum of the processing delays, propagation delays and queuing delays. The processing delay is the time required to process the packet header by nodes (i.e. IEDs, routers and switches). The propagation delay is time required to transfer/propagate a packet on the physical medium from one end to the other. The queuing delay is the time a packet waits in the buffer queue of a node. The queuing and processing delays constitute the major portion of ETE delay.

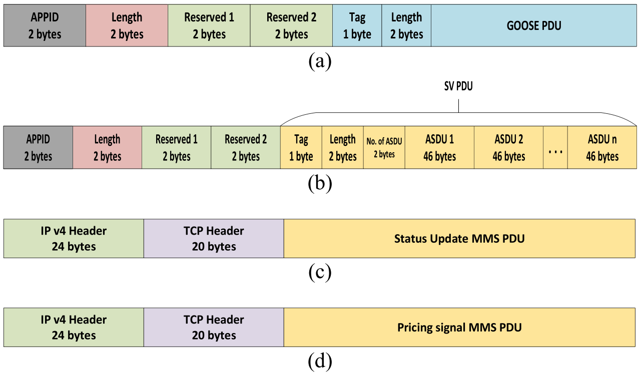

FIGURE 6. Frame formats of different messages. (a) Frame format of GOOSE APDU. (b) Frame format of Sample value APDU. (c) Frame format of Status update APDU. (d) Frame format of pricing signal APDU.

TABLE 5. Parameters of wireless technologies.

Parameters	WiMAX 802.16	WiFi 802.11g	WiFi 802.11n
Base Frequency	2.3 GHz	2.4 GHz	5.0 GHz
Data Rate	37 Mbps	54Mbps	65 Mbps
Channel Bandwidth	5 MHz	22 MHz	20/40 MHz
Modulation Type	OFDM	OFDM	OFDM-MIMO
Maximum Transmission power	20 W (base) 0.2 W (mobile)	0.1 W	0.1 W
FFT size	512	64	128
No. Sub carriers	192	52	114
Cyclic prefix duration	11.425µs	0.8 µs	0.8 µs

It is assumed that the ad-hoc microgrids are spread over an area of 0.5 km by 0.5 km and the UCD is located at a distance of 25 kms. Hence, in Riverbed Modeler the simulations project scenario with SHS microgrids spanning over 0.5 km by 0.5 km were simulated. The average distance between SHS/SM IED and access points was about 200-250 m. The UCD was connected to the base station access point over a wide area network with three hops. The simulations are carried out for Ethernet based LAN networks employing 100 Mbps and 1 Gbps links. Table 5 summarizes the different parameters of the wireless technologies used in the simulation of SHS based microgrid networks. The simulations were performed and ETE delays of different messages summarized in Table 4 for different communication technologies were collected.

For all SHS microgrid networks with varying sizes, ETE delays for status update and pricing signal messages obtained for different communication infrastructures are tabulated in Table 6. The ETE time delays of GOOSE messages, which are time critical, for different communication technologies

TABLE 6. ETE delay of status update and pricing signals for different SHS networks.

Type of Message → Communication Technologies ↓		Average Delay in seconds				
		LAN-100Mbps	LAN-1Gbps	WiFi-802.11n	WiFi-802.11g	WiMAX
100 SHS	Status Update	0.025	0.025	0.046	0.045	0.066
	Pricing signal	0.021	0.020	0.040	0.040	0.062
50 SHS	Status Update	0.017	0.017	0.032	0.035	0.049
	Pricing signal	0.011	0.011	0.030	0.032	0.044
20 SHS	Status Update	0.0063	0.0063	0.0076	0.0090	0.0295
	Pricing signal	0.0051	0.0051	0.0075	0.0088	0.0295
5 SHS	Status Update	0.0011	0.0011	0.0016	0.0025	0.0067
	Pricing signal	0.0009	0.0009	0.0012	0.0021	0.0060

TABLE 7. ETE delay of GOOSE messages for different SHS networks.

Communication Technologies ↓	Average Delay in milli seconds				
	LAN-100Mbps	LAN-1Gbps	WiFi-802.11n	WiFi-802.11g	WiMAX
100 SHS	0.22	0.21	1.00	1.60	2.55
50 SHS	0.14	0.14	0.75	0.80	1.40
20 SHS	0.08	0.08	0.42	0.48	0.95
5 SHS	0.03	0.03	0.13	0.17	0.23

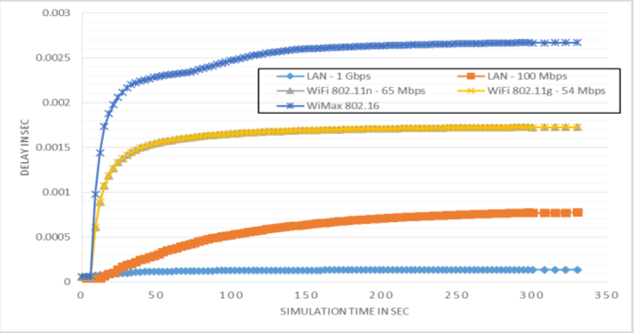

FIGURE 7. Comparison of Sample Values (SVs) delays for different communication technologies in 100 SHS microgrid networks.

(LAN, WiFi and WiMAX in different SHS microgrids) is tabulated in Table 7. The ETE delays for GOOSE messages for different communication technologies and different sizes of SHS are within the limits, i.e. 3 ms, as specified in the standards. The ETE delays for SV messages in 100 SHS networks is shown in Fig. 7. The ETE delays for SV and GOOSE messages are relatively lower with respect to pricing signal and status update messages due to the fact that these messages are exchanged between the SM and SHS, of a particular smart home system, which are on the same local area network or connected through a single access point. On the other hand, the pricing signals and status updates are exchanged between aggregator or UCD and SHS/SM which belong to different local area networks.

In a practical scenario, the network may include traffic sources other than the SHS. In order to include this in the simulation results, additional traffic sources have been added and their impact on the overall delay performance has been investigated.

Table 8 and 9 show increase in the ETE delays and average number of packet loss in the network for different type of messages when background traffic (of 1 Mbps and 10 Mbps) is introduced. This is due to the fact that, if the transmission of large client/server packet (i.e. background traffic) starts, then the other data packets has to wait in queue until this large packet is transmitted. The packet loss for status update, pricing signal and SVs with and without background traffic is presented in Table 9. As the GOOSE messages are brust type of messages and has negligible impact with respect to packet loss, hence GOOSE messages are omitted for packet loss analysis. The SV message the has highest packet loss since it has the highest sampling rates. High sampling rates results in high data traffic which inturn causes congestion in network which leads to packet drop or packet loss. From Table 9 it can be observed that SVs over WiFi 802.11G and 802.11n communication technologies has highest packet loss per second. It can be observed from the results that the wireless technologies (WiFi 802.11n, 802.11g and WiMAX) are more prone to packet loss due to poor SNR and external interferences. The packet loss analysis for pricing signal and status update messages is of parmount importance. Since the pricing signal and staus update messages use TCP in the transport layer, every packet that is lost has to be retransmitted. Hence, the packet loss in these type of messages results in retranmission of message and thereby considerably incresing the ETE delay.

From the results it is evident that LAN has low ETE delays and packet loss compared to WiFi and WiMAX networks. LAN is the best option for low-latency communication among SHSs as well as between SHSs and the utility. When the number of SHS increases, it may be costly as many switches and links are required. In LAN networks the signal is of good quality i.e. SNR ratio is very low. But, long physical links have risk of breakdown, hence wired networks are less preferable considering cost for remote locations of SHS based ad-hoc microgrids.

When SHS is used in a group or small communities, which results in few clusters, WiFi communication is advantageous. WiMAX is also good option for SHS clusters spread over a large area. But for SHS clusters in a small area WiMAX networks have relatively higher delays compared to WiFi networks. That's because, in WiMAX networks, receiving base stations have more subscribers since the range of WiMAX networks is comparatively large. While in WiFi networks, receivers are available for every cluster, hence the queuing of data in receiver's buffer is less. Thus, queuing of data in WiMAX network causes increased processing time and delay.

TABLE 8. ETE delay of different messages for different SHS networks under background traffic.

Communication Technologies → Type of Message ↓		Average Delay in seconds									
		Background Traffic (1 Mbps)					Background Traffic (10 Mbps)				
		LAN-100Mbps	LAN-1Gbps	WiFi-802.11n	WiFi-802.11g	WiMAX	LAN-100Mbps	LAN-1Gbps	WiFi-802.11n	WiFi-802.11g	WiMAX
100 SHS	Status Update	0.033	0.027	0.048	0.049	0.066	0.043	0.029	0.055	0.058	0.083
	Pricing signal	0.031	0.027	0.040	0.042	0.063	0.036	0.029	0.057	0.058	0.084
	GOOSE	0.00029	0.00023	0.0013	0.0017	0.0031	0.00037	0.00024	0.0022	0.0028	0.004
	SV	0.00078	0.00049	0.0018	0.00018	0.0028	0.001	0.00065	0.0030	0.0030	0.0033
50 SHS	Status Update	0.022	0.018	0.034	0.035	0.049	0.028	0.019	0.042	0.045	0.053
	Pricing signal	0.022	0.016	0.031	0.032	0.044	0.027	0.015	0.040	0.042	0.051
	GOOSE	0.00019	0.00015	0.0008	0.00082	0.0016	0.00023	0.00019	0.0017	0.0019	0.0023
	SV	0.00042	0.00029	0.0014	0.00014	0.0018	0.00088	0.00043	0.0021	0.00021	0.0027
20 SHS	Status Update	0.0068	0.0065	0.0077	0.0095	0.0308	0.0076	0.0069	0.0088	0.013	0.033
	Pricing signal	0.0056	0.0053	0.0075	0.0094	0.0301	0.0064	0.0060	0.0085	0.011	0.032
	GOOSE	0.00011	0.00009	0.00052	0.00057	0.001	0.0002	0.0001	0.0008	0.00095	0.0014
	SV	0.00023	0.00019	0.00081	0.00083	0.00097	0.0003	0.00023	0.0013	0.0012	0.0016
5 SHS	Status Update	0.0014	0.0011	0.0022	0.0031	0.0067	0.0021	0.0014	0.0029	0.0042	0.0085
	Pricing signal	0.0011	0.0009	0.0021	0.0030	0.0065	0.0019	0.0013	0.0028	0.0042	0.0083
	GOOSE	0.00004	0.00003	0.00014	0.00017	0.00026	0.00007	0.00004	0.00020	0.00023	0.00039
	SV	0.00008	0.00006	0.0003	0.00032	0.00039	0.0001	0.00007	0.0008	0.0008	0.001

TABLE 9. Packet loss of different messages for different SHS networks with and without background traffic of 10 Mbps.

Communication Technologies → Type of Message ↓		Average number of Packet Loss per second									
		LAN-100Mbps		LAN-1Gbps		WiFi-802.11n		WiFi-802.11g		WiMAX	
		Without Background Traffic	With Background Traffic	Without Background Traffic	Without Background Traffic	Without Background Traffic	With Background Traffic	Without Background Traffic	With Background Traffic	Without Background Traffic	With Background Traffic
100 SHS	Status Update	7	11	7	9	15	17	16	19	11	11
	Pricing signal	7	11	7	9	15	17	16	19	11	11
	SV	18	21	14	16	28	33	31	33	22	26
50 SHS	Status Update	6	8	6	8	9	10	9	10	8	9
	Pricing signal	6	8	6	8	9	10	9	10	8	9
	SV	13	19	8	10	19	22	19	22	14	16
20 SHS	Status Update	3	3	3	3	5	7	6	9	5	5
	Pricing signal	3	3	3	3	5	7	6	9	5	5
	SV	4	4	3	4	4	6	4	6	3	4
5 SHS	Status Update	1	3	1	2	1	3	2	4	3	3
	Pricing signal	1	3	1	1	1	3	2	4	3	3
	SV	2	3	2	2	3	4	3	3	2	3

VI. CONCLUSIONS

In order to ensure interoperability between devices from different manufacturers, IEC 61850 communication standard is utilized for common information modeling. Different components such as distributed generators, fault current limiters and electric vehicles have been modeled according to the said standard. However, despite their recent popularity, SHS and SM are yet to be added to this collection. In this respect, this work makes a significant contribution to the body of knowledge for future interoperability and modeling of microgrids.

With focus on extraction of renewable energy resources, SHS are becoming popular distributed remote generations. These systems can remain independent as well as they can interact with power grid to feed or take power. This bi-directional flow is being controlled and monitored by SHS user and distant utility. The communication model of SHS is proposed with its functions focused on interaction with power grid as SH2G technology. A new LN class SHCT is defined for SHS as per IEC 61850-7-420. The SM is critical part in communication process between power utility and consumer end. Detailed modeling of SM with its functions is done based on IEC 61850 standard. This modeling will help in deployment of SMs with dynamic power flow. Also, smart pricing and demand side management concepts are integrated to this model to advance applicability of SMs.

Integration of SHS and SM into smart grid and ensuring a standard interaction is vital for the success of power grid revolution. This paper makes a significant contribution to the body of knowledge by developing separate models for each of these components. These models are specifically developed to cater for different operating modes and functionalities that may be needed in future grids.

In order to test the performance of these models over different communication technologies, extensive simulations have been developed and run in Riverbed Modeler. Based on the results, it can be concluded that the performances of wireless technologies (WiMAX & WiFi) and Ethernet satisfy IEC 61850 requirements for smart grids. The performance of developed communication models is satisfactory and meets IEC requirements, even under different factors effecting the network, such as other traffic sources (background traffic) and packet loss. These results are important for real-life implementation of developed standard models and achieving PnP in power networks.

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S. M. SUHAIL HUSSAIN (S'11) received the B.Tech. degree in electrical and electronics engineering from Sri Venkateswara University, Tirupati, India, in 2010, and the M.Tech. degree from Jawaharlal Nehru Technological University, Anantapur, India, in 2013. He is currently pursuing the Ph.D. degree in electrical engineering with Jamia Millia Islamia, New Delhi, India. His research interests include microgrid, power system communications, and smart grid. He was a recipient of the IEEE Standards Education Grant approved by the IEEE Standards Education Committee for implementing project and submitting a student application paper in 2014–2015.

ASHOK TAK received the B.Tech. degree in electrical engineering from IIT Roorkee, Roorkee, India, in 2016. He was a Summer Research Intern with Carnegie Mellon University in 2015. He is currently with the Load Dispatch Center, Electrical T&D, Tata Steel Ltd., India. He is interested in smart microgrids, renewable energy integration, power system real time digital simulation, IEC 61850, and smart grid communication.

TAHA SELIM USTUN received the Ph.D. degree in electrical engineering from Victoria University, Melbourne, VIC, Australia. He was an Assistant Professor of electrical engineering with the Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA. He is currently a Research Scientist with the Fukushima Renewable Energy Institute, AIST, Japan. He has over 40 publications that appeared in international peer-reviewed journals and conferences. His research interests include power systems protection, communication in power networks, distributed generation, micrograds, and smartgrids. He is a reviewer in reputable journals and has taken active roles in organizing international conferences and chairing sessions. He delivered talks for World Energy Council, Waterloo Global Science Initiative, European Union Energy Initiative and the Qatar Foundation. He has also been invited to run short courses in Africa, India, and China.

IKBAL ALI (M'04–SM'11) received the degree from Aligarh Muslim University, Aligarh, the M.Tech. degree from IIT Roorkee, Roorkee, India, and the Ph.D. degree in electrical engineering. He is currently an Associate Professor with the Department of Electrical Engineering, Jamia Millia Islamia, New Delhi. As a Principle Investigator, he is executing research projects on substation automation, micro-grid, and IEC 61850-based utility automation funded from DST, AICTE, JMI, and IEEE Standards Education Society. His research interests are in IEC 61850-based utility automation, substation communication networks architecture, and smart grid.

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