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IEC 61850 Modeling of UPFC and XMPP Communication for Power Management in Microgrids

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ABSTRACT Integration of distributed renewable energy sources in microgrids presents many challenges to grid such as voltage, stability and power management issues. In literature different control strategies to improve the performance of microgrids integrated with renewable energy sources proposed. FACTS based controller such as Unified Power Flow Controller (UPFC) has also been employed in microgrids to improve the power management and transient stability. Coordinated control strategies between UPFC controller and DERs have been developed. However, the underlying communication for realizing these strategies has not been discussed. This paper presents IEC 61850 and XMPP based communication for coordinating UPFC and DERs in microgrid for its stable operation. IEC 61850 information model for UPFC controller is developed. Furthermore, the XMPP protocol is utilized to provide the scalability for communication network in microgrids with high penetration of DERs. Additionally, XMPP also provides improved security along with the scalability. IEC 61850 message exchanges over XMPP communication between different components of microgrid for power management is demonstrated.

INDEX TERMS Unified power flow controller (UPFC), IEC 61850, extensible messaging and presence protocol (XMPP), microgrids.

I. INTRODUCTION

Due to the impetus towards the use of clean technologies for power generation, there is steady increase in use of renewable energy sources in power grids. Renewable energy sources provide clean electricity at lower costs compared to other fossil fuel-based generation systems. However, the renewable energy sources heavily depend on environmental factors for power generation making it intermittent. Due to this intermittent nature, renewable energy sources present many challenges for their smooth integration to grid [1].

To address the challenges of grid integration of intermittent renewable and Distributed Energy Sources (DERs) the concepts such as microgrids, Virtual Power Plant are introduced by researchers [2], [3]. In microgrids, due to presence of intermittent renewable energy sources, the transient stability and power management are important factors. In literature, researchers have provided many solutions for improving the power management and transient stability of microgrids with high penetration of renewable DERs [4], [5]. One of the solutions, Unified Power Flow Controller (UPFC) is utilized in microgrids for improving the transient stability and power management [6], [7]. To achieve effective control, a coordinated control mechanism for UPFC and DERs in microgrid is required. In [6], authors present a control mechanism for effectively controlling the DERs and UPFC in microgrids. However, the underlying communication mechanism to realize this control is not discussed.

Communication plays a vital role in realizing and deploying the coordinated control strategies successfully. An interoperable and standardized communication is required for its smooth deployment. In this regard, IEC 61850 standard provides a promising solution for developing interoperable and standardized communication for microgrids [8]. IEC 61850 based interoperable communication models for different components of power utility system are well studied in literature, such as different DERs [9], Smart Home Systems [10], EV [11], energy router [12]. In this paper, adopting the similar approach IEC 61850 information model of UPFC controller is developed.

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Furthermore, utilizing the developed IEC 61850 information model of UPFC, the communication mechanism for realizing power management in microgrid is presented. Due to intermitted power generation of renewable DERs, their connection to grid is highly stochastic. In order to accommodate the stochastic nature of DERs and improve scalability of microgrid communication network, eXtensible Messaging and Presence Protocol (XMPP) web protocol is chosen for microgrid communication network. XMPP protocol is a web-based protocol at transport layer providing high scalability. Additionally, XMPP protocol provides improved security i.e. a two-layer security mechanism. Hence, in this paper, XMPP based IEC 61850 communication is utilized for achieving microgrid power management. The IEC 61850 messages exchanged between microgrid central controller (MGCC), UPFC and DERs over XMPP protocol are demonstrated.

The rest of the paper is organized as follows. Section II presents a brief overview of UPFC and IEC 61850 based information modeling of UPFC controller. Section III presents the communication message exchanges for achieving power management n microgrid. Section IV presents overview of XMPP communication and demonstration of IEC 61850 message exchanges over XMPP in microgrid. Finally, section V concludes the paper.

II. MODELING OF UPFC

A. OVERVIEW OF UPFC

Due to its versatile functions UPFC is regarded as one of the important FACTS devices. UPFC is combination of two FACTS devices STATCOM and SSSC. UPFC consists of two voltage source converters (VSC) connected though a dc capacitor link. One VSC is connected in shunt and other one is connected in series via shunt and series transformers as shown in Fig. 1. VSC connected in shunt acts as a DSTATCOM.

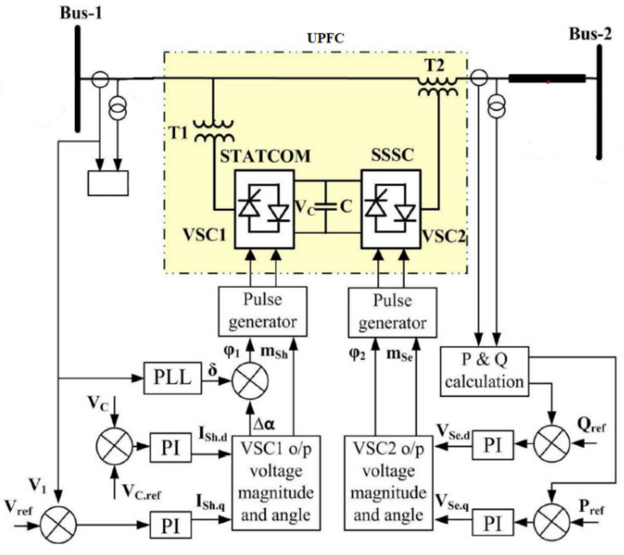


FIGURE 1. Block diagram of UPFC.

The VSC1 i.e. shunt converter provides reactive power compensation by absorbing or generating reactive power. The VSC2 provides a series voltage injection which results in exchange of active and reactive power. The real power delivered/absorbed by VSC2 appears as dc power demand at dc link. This power demand on dc link is supplied/absorbed by the VSC1. Thus, active power demand of VSC2 is supplied/absorbed by VSC1 via the dc link. However, the reactive doesn't flow through the dc link, only real power flows through the dc link. The reactive power is managed, either absorbed or supplied, independently at each VSC.

Thus, the UPFC provides shunt reactive power compensation at VSC1 (shunt connection) and ability to control active and reactive power flow at VSC2 (series connection).

B. IEC 61850 INFORMATION MODELING OF UPFC CONTROLLER IED

Information modeling is a method of providing standardized syntax, semantics and hierarchical structures to the data that is exchanged among different devices and systems. In IEC 61850, the information modeling is achieved by defining logical nodes and Data Objects (DOs). Logical nodes are group of DOs which serve specific function and are defined conceptually in IEC 61850. Combination of several logical nodes form a logical device and interact with each other in accordance with a set of rules defined by the standard.

Information modeling of UPFC requires that the specific process variable data exchanges, occurring in the UPFC controller, to be modeled as instance of the logical nodes. The process variables are reference settings and control signals which are either exchanged or provided to the UPFC controller. These process variables are incorporated in the logical node models as the DOs which serve specific functions. Fig. 2 shows logical nodes used for UPFC controller modeling. The LNs TCTR, TVTR and MMXU correspond to the measuring devices. The TVTR and TCTR nodes provides interface for voltage and current measurements, MMXU is used for reporting currents, voltages, powers, frequency and impedance values.

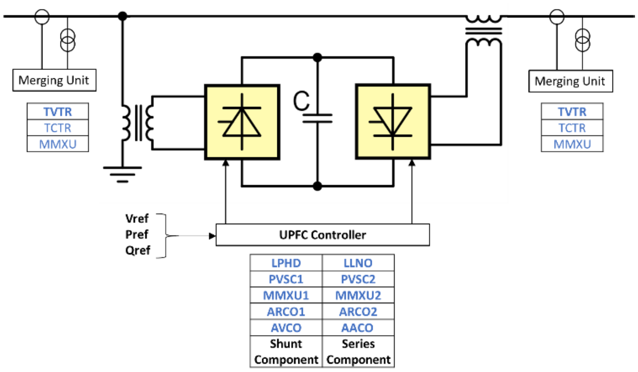


FIGURE 2. IEC 61850 information model of UPFC.

The UPFC controller is virtually split into two parts i.e. STATCOM controller and SSSC controller. The STATCOM part of UPFC controller is modelled with the ARCO, AVCO, PVSC and MMXU logical nodes. The modeling of STATCOM part of UPFC controller is on similar lines of DSTATCOM controller information model developed in [13]. The LN AVCO contains the information of DOs associated with voltage control of VSC (STATCOM) of UPFC. The DO 'Vspt' of LN AVCO contains the information of voltage reference point for STATCOM part of UPFC controller. The logical node ARCO contains the semantics required for reactive power compensation by STATCOM. The DO 'Qspt' of LN ARCO contains the information of reactive power reference for STATCOM part of UPFC controller. The LN PVSC corresponds to the protection of VSC. The description of LNs AVCO, ARCO and PVSC is given in Table 1, 2 and 3 respectively.

TABLE 1. Automatic voltage control (AVCO) logical node [13].

AVCO Class				
DO Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from the logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		
Settings				
Vlin	ASG	Acquires voltage value from the TVTR class		M
LimAoV	ASG	Specifies limit of operation for current		M
LimVoV	ASG	Specifies limit of operation for voltage		M
Aspt	ASG	Set point for the current		M
Vspt	ASG	Set point for the voltage		M
TapChg	BSC	Change voltage value		M
LoC	SPS	Local operation		O

**CDC-Common Data Class, *T-Transient data objects, *M-mandatory, *O-Optional, *C-Conditional, *ASG-Analog Setting Group, *BSC-Binary controlled step position information, *SPS-Single Point Status*

The SSSC part of UPFC is modeled with ARCO, PVSC and AACO LNs. The PVSC LN is associated with protection of VSC related to SSSC part of UPFC. The ARCO LN relates to reactive power compensation is similar to that defined for STATCOM part. The SSSC part of UPFC controller contains an additional node AACO which contains the semantics related to active power by SSSC. This is a new LN model developed in this paper. The DO "Pspt" gives the information regarding active power set point for SSSC part for UPFC controller. The Dos 'LimPoV' and 'LimAoV' corresponds to the active power and current limits. The description of Dos corresponding AACO LN model is given in Table 4.

III. POWER MANAGEMENT USING UPFC IN MICROGRIDS

The UPFC has been used in microgrids for voltage profile improvement, reactive and active power compensation [7], [14], [15]. In microgrid with high penetration of distributed renewable energy sources (DERs) the power generation is intermittent. Hence, a coordinated operation of UPFC and DERs is required for effective power management and voltage profile improvement. The coordinated operation of UPFC is advantageous than local control of UPFC.

TABLE 2. Automatic reactive power compensation (ARCO) logical node [13].

ARCO Class				
DO Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from the logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		
Settings				
LimAoV	ASG	Specifies limit of operation for current		M
Lim QoV	ASG	Specifies limit of operation for reactive power		M
Qspt	ASG	Set point for reactive power		M
Gainspt	ASG	Setting for Gain of the controller		M
Slopespt	ASG	Set point for slope correction		M
TapChg	BSC	Change reactive power		M
LoC	SPS	Local operation		O

**CDC-Common Data Class, *T-Transient data objects, *M-mandatory, *O-Optional, *C-Conditional *ASG-Analog Setting Group, *BSC-Binary controlled step position information, *SPS-Single Point Status*

TABLE 3. Protection for voltage source converter (PVSC) logical node [13].

PVSC Class				
DO Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from the logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		
Settings				
LimVSC	ASG	Specifies limit for primary current of VSC		O
StrValVSC	APC	Overload limit value		O
OpVSC	APC	Operating range maximum value		O
Str	ACD	Starting of device		M
Opt	ACT	Operation of device		M

**CDC-Common Data Class, *T-Transient data objects, *M-mandatory, *O-Optional, *C-Conditional*ASG-Analog Setting Group, *APC-Controllable analogue set point information, *ACD-Directional protection activation information, *ACT-Protection activation information*

The Microgrid Central Controller (MGCC) coordinates the operation of UPFC and DERs through a standardized communication. UPFC requires three input parameters i.e. voltage reference point for shunt connection and active and reactive power reference point for series connection. These reference points are provided by MGCC thorough a power management scheme.

Two components of UPFC are utilized for two distinct operations. Shunt connection, i.e. STATCOM, is utilized to meet local reactive power demand and maintain unity power factor at the point of utility connection.

TABLE 4. Automatic active power compensation (AACO) logical node.

AACO Class				
DO Name	**CDC**	**Explanation**	**T**	**M/O/C**
LNName		Shall be inherited from the logical-node class (see IEC 61850-7-2)		
Data				
System logical node data				
		LN shall inherit all mandatory data from common logical node class		
Settings				
LimAoV	ASG	Specifies limit of operation for current		M
Lim PoV	ASG	Specifies limit of operation for active power		M
Pspt	ASG	Set point for active power		M
TapChg	BSC	Change active power		M
LoC	SPS	Local operation		O

**CDC-Common Data Class, *T-Transient data objects, *M-mandatory, *O-Optional, *C-Conditional *ASG-Analog Setting Group, *BSC-Binary controlled step position information, *SPS-Single Point Status*

Series connection, i.e. SSSC, on the other hand, is utilized to provide auxiliary support for local voltage and frequency control. In line with recent developments, grids require distributed generators to provide such services to mitigate their negative impacts [16], [17]. SSSC is utilized to implement such a control technique called Volt-Var control [18]. However, implementations are not limited by this and can be extended to different modes. MGCC sends control signals to series connection to keep the local voltage and frequency within permissible conditions and maximize power generation.

The voltage reference point (v_{ref}) for shunt connection (STATCOM) of UPFC is given in equation

$$\begin{aligned} v_{ref} = v_o - mQ_{STATCOM} + k_1 \frac{R_1P_1 + X_1Q_1}{V_{11}V_{22}} [S_1] \\ + k_2 \frac{R_2P_2 + X_2Q_2}{V_{22}V_{33}} [S_2] + \ldots \\ + k_i \frac{R_iP_i + X_iQ_i}{V_{ii}V_{i+1,i+1}} [S_i] + \ldots \\ + k_n \frac{R_nP_n + X_nQ_n}{V_{nn}V_{n+1,n+1}} [S_p] \end{aligned}$$

where v_o is the nominal voltage of the particular bus to which shunt terminal of UPFC is connected, m is the slope of droop curve of the shunt VSC of UPFC interfaced to the DER and K_n is the proportionality factor for each DER and [s] is status matrix given as,

$$[S] = [1 \quad 0 \quad 0 \quad \ldots\ldots \quad 1 \quad 1 \quad \ldots]^T$$

where 1s and 0s indicate the status of DERs as on and off respectively. The number of elements contained in the status matrix is governed by the number of DERs in a microgrid.

For controlling series connection, SSSC, Volt-Var curves defined in IEC 61850-90-7 are used, shown in Fig. 3. *VRef* is nominal voltage of the power system while *VarAval* is maximum var output with no impact on watts. These curves are stipulated on distributed generators and help improve the power system stability. Therefore, their implementation with UPFC and MGCC is vital for keeping system stability while increasing renewable energy penetration levels.

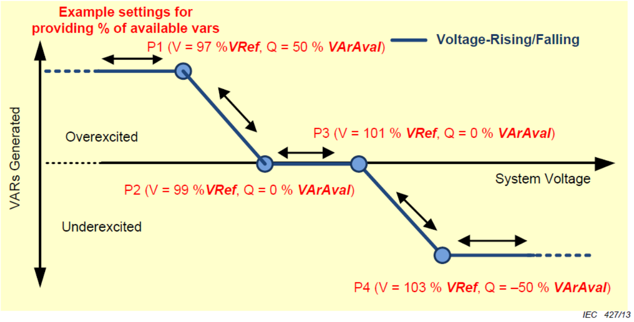


FIGURE 3. Volt-Var curves for grid support by distributed generators.

MGCC receives local voltage measurements and calculate the required reactive power to keep voltage within permissible limits. It sends active and reactive power reference points (P_{ref}, Q_{ref}) to the SSSC part of UPFC. Active power reference point can be utilized for other implementations.

The information exchanges between MGCC, DER and UPFC controller required for realizing the power management in microgrid are summarized in Table 5. Table 5 also provides the type of IEC 61850 message used to communication the particular information.

TABLE 5. Information exchanges for power management in microgrid.

Information Exchange	Source	Destination	IEC 61850 message Type
Connection Status of DERs [*S*]	DERs	MGCC	MMS
Voltage, Active and Reactive power generation at DERs V_i, P_i, Q_i	DERs	MGCC	MMS
Set points for active and reactive power generation	MGCC	DERs	MMS
$v_{ref}, P_{ref}, Q_{ref}$	MGCC	UPFC	MMS

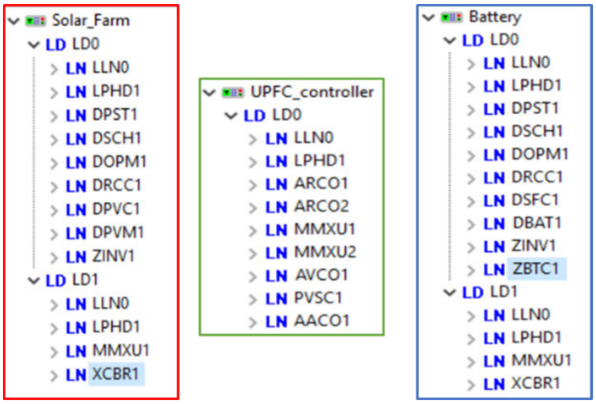
IV. IEC 61850 BASED COMMUNICATION CONFIGURATION

The IEC 61850 information model for UPFC controller is developed in section II. In this paper, IEC 61850 information model for DERs is adopted from model developed in [9]. The information model of DER contains the common LNs DOPA, DOPM, DPST, DCCT, DSCH, DRCS, and DRCC. The LN DPST contains a DO ''ECP Conn'' which provides the real-time connection status and measurements at ECP.

The information exchange and data flow for power management in microgrids is demonstrated in this section. The MGCC communicates with different DER and UPFC controllers to provide reference points for their operation. The IEC 61850 messages communicated over XMPP protocol.

A. IEC 61850 MODELING AND INFORMATION EXCHANGES

Firstly, information models of these components have been developed based on IEC 61850's common information model (CIM). As shown in Figure 4, three different components are constructed: Solar Farm (i.e. DERs), battery and UPFC controller. MGCC knows these configurations and sends relevant instructions accordingly.



```
Solar_Farm
  LD LD0
    LN LLN0
    LN LPHD1
    LN DPST1
    LN DSCH1
    LN DOPM1
    LN DRCC1
    LN DPVC1
    LN DPVM1
    LN ZINV1
  LD LD1
    LN LLN0
    LN LPHD1
    LN MMXU1
    LN XCBR1
```

```
UPFC_controller
  LD LD0
    LN LLN0
    LN LPHD1
    LN ARCO1
    LN ARCO2
    LN MMXU1
    LN MMXU2
    LN AVCO1
    LN PVSC1
    LN AACO1
```

```
Battery
  LD LD0
    LN LLN0
    LN LPHD1
    LN DPST1
    LN DSCH1
    LN DOPM1
    LN DRCC1
    LN DSFC1
    LN DBAT1
    LN ZINV1
    LN ZBTC1
  LD LD1
    LN LLN0
    LN LPHD1
    LN MMXU1
    LN XCBR1
```

FIGURE 4. IEC 61850 modeling of DER1 (solar farm), UPFC controller and Battery system.

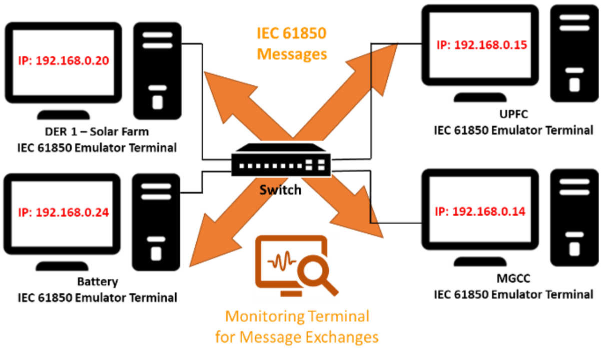
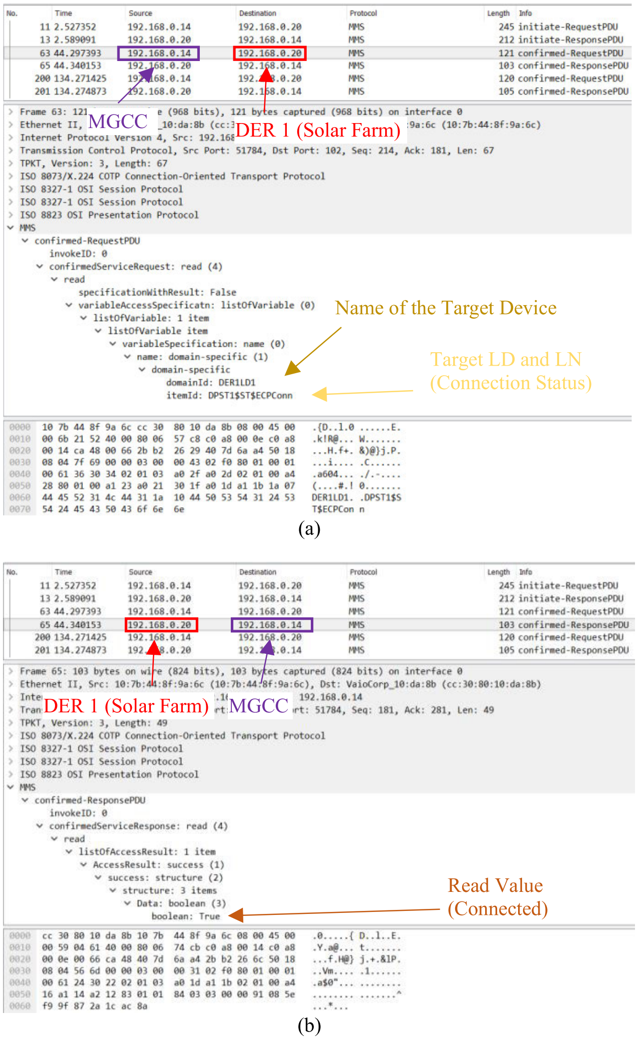


FIGURE 5. Lab test configuration for validation of IEC 61850 models and messages.

In order to validate these information models a test configuration in developed as shown in Figure 5. MGCC sends messages to gather information and instruct operating conditions. These IEC 61850 messages are monitored with an additional terminal while the results of the intended operation are verified in target nodes. For instance, MGCC can send a command to DER1 to check its connection status. This *real* message is constructed and sent as shown in Figure 6. The response message is sent from DER1 as *true,* indicating that it is connected to the electrical network. These are the messages sent by MGCC and DER1, respectively, and they are monitored on the network. The corresponding variables and their values are also verified within these terminals, using the models shown in Figure 4.



```
No.   Time          Source          Destination     Protocol   Length Info
   11 2.527352      192.168.0.14    192.168.0.20    MMS           245 initiate-RequestPDU
   13 2.589091      192.168.0.20    192.168.0.14    MMS           212 initiate-ResponsePDU
   63 44.297393     192.168.0.14    192.168.0.20    MMS           121 confirmed-RequestPDU
   65 44.340153     192.168.0.20    192.168.0.14    MMS           103 confirmed-ResponsePDU
  200 134.271425    192.168.0.14    192.168.0.20    MMS           120 confirmed-RequestPDU
  201 134.274873    192.168.0.20    192.168.0.14    MMS           105 confirmed-ResponsePDU
```

```
> Frame 63: 121          e (968 bits), 121 bytes captured (968 bits) on interface 0
> Ethernet II,           _10:da:8b (cc:3                          :9a:6c (10:7b:44:8f:9a:6c)
> Internet Protocol Version 4, Src: 192.168
> Transmission Control Protocol, Src Port: 51784, Dst Port: 102, Seq: 214, Ack: 181, Len: 67
> TPKT, Version: 3, Length: 67
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-RequestPDU
      invokeID: 0
    v confirmedServiceRequest: read (4)
      v read
          specificationWithResult: False
        v variableAccessSpecificatn: listOfVariable (0)
          v listOfVariable: 1 item
            v listOfVariable item
              v variableSpecification: name (0)
                v name: domain-specific (1)
                  v domain-specific
                      domainId: DER1LD1
                      itemId: DPST1$ST$ECPConn
```

```
0000  10 7b 44 8f 9a 6c cc 30  80 10 da 8b 08 00 45 00   .{D..l.0 ......E.
0010  00 6b 21 52 40 00 80 06  57 c8 c0 a8 00 0e c0 a8   .k!R@... W.......
0020  00 14 ca 48 00 66 2b b2  26 29 40 7d 6a a4 50 18   ...H.f+. &)@}j.P.
0030  08 04 7f 69 00 00 03 00  00 43 02 f0 80 01 00 01   ...i.... .C......
0040  00 61 36 30 34 02 01 03  a0 2f a0 2d 02 01 00 a4   .a604... ./.-....
0050  28 80 01 00 a1 23 a0 21  30 1f a0 1d a1 1b 1a 07   (....#.! 0.......
0060  44 45 52 31 4c 44 31 1a  10 44 50 53 54 31 24 53   DER1LD1. .DPST1$S
0070  54 24 45 43 50 43 6f 6e  6e                        T$ECPCon n
```

(a)

```
No.   Time          Source          Destination     Protocol   Length Info
   11 2.527352      192.168.0.14    192.168.0.20    MMS           245 initiate-RequestPDU
   13 2.589091      192.168.0.20    192.168.0.14    MMS           212 initiate-ResponsePDU
   63 44.297393     192.168.0.14    192.168.0.20    MMS           121 confirmed-RequestPDU
   65 44.340153     192.168.0.20    192.168.0.14    MMS           103 confirmed-ResponsePDU
  200 134.271425    192.168.0.14    192.168.0.20    MMS           120 confirmed-RequestPDU
  201 134.274873    192.168.0.20    192.168.0.14    MMS           105 confirmed-ResponsePDU
```

```
> Frame 65: 103 bytes on wire (824 bits), 103 bytes captured (824 bits) on interface 0
> Ethernet II, Src: 10:7b:44:8f:9a:6c (10:7b:44:8f:9a:6c), Dst: VaioCorp_10:da:8b (cc:30:80:10:da:8b)
> Inte                     .1                192.168.0.14
> Tran                     rt                rt: 51784, Seq: 181, Ack: 281, Len: 49
> TPKT, Version: 3, Length: 49
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-ResponsePDU
      invokeID: 0
    v confirmedServiceResponse: read (4)
      v read
        v listOfAccessResult: 1 item
          v AccessResult: success (1)
            v success: structure (2)
              v structure: 3 items
                v Data: boolean (3)
                    boolean: True
```

```
0000  cc 30 80 10 da 8b 10 7b  44 8f 9a 6c 08 00 45 00   .0.....{ D..l..E.
0010  00 59 04 61 40 00 80 06  74 cb c0 a8 00 14 c0 a8   .Y.a@... t.......
0020  00 0e 00 66 ca 48 40 7d  6a a4 2b b2 26 6c 50 18   ...f.H@} j.+.&lP.
0030  08 04 56 6d 00 00 03 00  00 31 02 f0 80 01 00 01   ..Vm.... .1......
0040  00 61 24 30 22 02 01 03  a0 1d a1 1b 02 01 00 a4   .a$0"... ........
0050  16 a1 14 a2 12 83 01 01  84 03 03 00 00 91 08 5e   ........ .......^
0060  f9 9f 87 2a 1c ac 8a                               ...*...
```

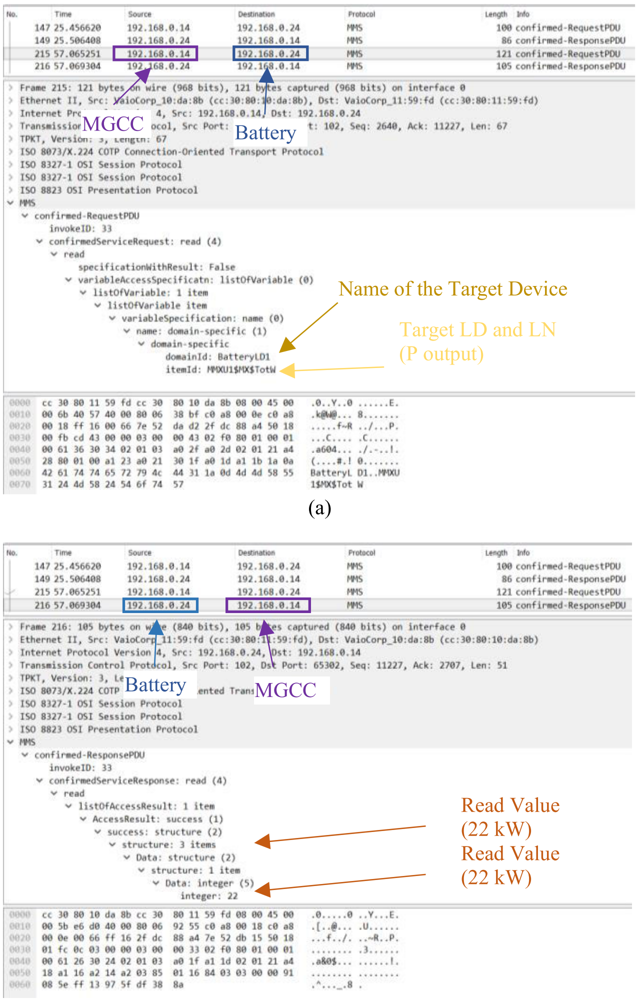
(b)

FIGURE 6. MGCC getting status of DER1 (solar farm).

A similar operation is shown for the battery in Figure 7. MGCC sends a request command to learn active power output of the battery storage system. As shown, MGCC polls BatteryLD1's MMXUMXTotW data object. Battery responds with a message indicating that the current active power output is 22kW. Again, transmission of *real* messages and values of corresponding variables are verified.

Based on these readings, MGCC is supposed to make decisions and send instructions to the UPFC. For instance, as shown in Figure 8, MGCC may send a voltage set point to UPFC's shunt component, i.e. STATCOM, to keep it constant. In this case, UPFC is instructed to keep the voltage at 1 p.u. In addition to message exchanges in the network, it is also verified that this instruction is properly received by the UPFC model and voltage setpoint, i.e. AVCOSTVspt$stVal, is set as 1.

UPFC's series component, i.e. SSSC, used to implement Volt-Var support as explained in the previous section. Depending on the circumstances, and operating curves, MGCC calculates the required reactive power output and instructs UPFC to realize this exchange. Figure 9 shows that



```
No.    Time         Source         Destination    Protocol   Length Info
   147 25.456620    192.168.0.14   192.168.0.24   MMS           100 confirmed-RequestPDU
   149 25.506408    192.168.0.24   192.168.0.14   MMS            86 confirmed-ResponsePDU
   215 57.065251    192.168.0.14   192.168.0.24   MMS           121 confirmed-RequestPDU
   216 57.069304    192.168.0.24   192.168.0.14   MMS           105 confirmed-ResponsePDU

> Frame 215: 121 bytes on wire (968 bits), 121 bytes captured (968 bits) on interface 0
> Ethernet II, Src: VaioCorp_10:da:8b (cc:30:80:10:da:8b), Dst: VaioCorp_11:59:fd (cc:30:80:11:59:fd)
> Internet Pro          4, Src: 192.168.0.14, Dst: 192.168.0.24
> Transmission      ocol, Src Port:              t: 102, Seq: 2640, Ack: 11227, Len: 67
> TPKT, Version: 3, Length: 67
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-RequestPDU
      invokeID: 33
    v confirmedServiceRequest: read (4)
      v read
          specificationWithResult: False
        v variableAccessSpecificatn: listOfVariable (0)
          v listOfVariable: 1 item
            v listOfVariable item
              v variableSpecification: name (0)
                v name: domain-specific (1)
                  v domain-specific
                      domainId: BatteryLD1
                      itemId: MMXU1$MX$TotW

0000  cc 30 80 11 59 fd cc 30  80 10 da 8b 08 00 45 00   .0..Y..0 ......E.
0010  00 6b 40 57 40 00 80 06  38 bf c0 a8 00 0e c0 a8   .k@W@... 8.......
0020  00 18 ff 16 00 66 7e 52  da d2 2f dc 88 a4 50 18   .....f~R ../...P.
0030  00 fb cd 43 00 00 03 00  00 43 02 f0 80 01 00 01   ...C.... .C......
0040  00 61 36 30 34 02 01 03  a0 2f a0 2d 02 01 21 a4   .a604... ./.-..!.
0050  28 80 01 00 a1 23 a0 21  30 1f a0 1d a1 1b 1a 0a   (....#.! 0.......
0060  42 61 74 74 65 72 79 4c  44 31 1a 0d 4d 4d 58 55   BatteryL D1..MMXU
0070  31 24 4d 58 24 54 6f 74  57                        1$MX$Tot W
```

(a)

```
No.    Time         Source         Destination    Protocol   Length Info
   147 25.456620    192.168.0.14   192.168.0.24   MMS           100 confirmed-RequestPDU
   149 25.506408    192.168.0.24   192.168.0.14   MMS            86 confirmed-ResponsePDU
   215 57.065251    192.168.0.14   192.168.0.24   MMS           121 confirmed-RequestPDU
   216 57.069304    192.168.0.24   192.168.0.14   MMS           105 confirmed-ResponsePDU

> Frame 216: 105 bytes on wire (840 bits), 105 bytes captured (840 bits) on interface 0
> Ethernet II, Src: VaioCorp_11:59:fd (cc:30:80:11:59:fd), Dst: VaioCorp_10:da:8b (cc:30:80:10:da:8b)
> Internet Protocol Version 4, Src: 192.168.0.24, Dst: 192.168.0.14
> Transmission Control Protocol, Src Port: 102, Dst Port: 65302, Seq: 11227, Ack: 2707, Len: 51
> TPKT, Version: 3, Le
> ISO 8073/X.224 COTP           ented Trans
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-ResponsePDU
      invokeID: 33
    v confirmedServiceResponse: read (4)
      v read
        v listOfAccessResult: 1 item
          v AccessResult: success (1)
            v success: structure (2)
              v structure: 3 items
                v Data: structure (2)
                  v structure: 1 item
                    v Data: integer (5)
                        integer: 22

0000  cc 30 80 10 da 8b cc 30  80 11 59 fd 08 00 45 00   .0.....0 ..Y...E.
0010  00 5b e6 d0 40 00 80 06  92 55 c0 a8 00 18 c0 a8   .[..@... .U......
0020  00 0e 00 66 ff 16 2f dc  88 a4 7e 52 db 15 50 18   ...f../. ..~R..P.
0030  01 fc 0c 03 00 00 03 00  00 33 02 f0 80 01 00 01   ........ .3......
0040  00 61 26 30 24 02 01 03  a0 1f a1 1d 02 01 21 a4   .a&0$... ......!.
0050  18 a1 16 a2 14 a2 03 85  01 16 84 03 03 00 00 91   ........ ........
0060  08 5e ff 13 97 5f df 38  8a                        .^..._.8 .
```

(b)

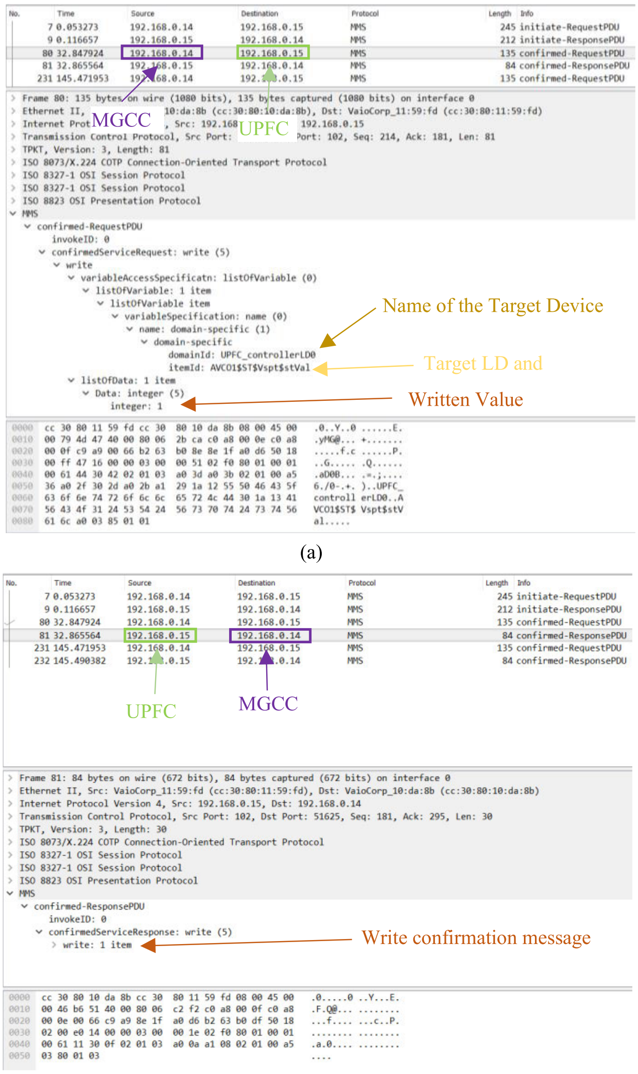
FIGURE 7. MGCC getting active power generation value at battery.

UPFC's VAR output is set to 32 %, in order to support the local voltage.

The tests performed in this section are vital for validating the developed models and verify proper exchange of IEC 61850 messages. It is also confirmed that these messages are reflected on operating modes or set points. Once these tests are confirmed, the system is extended to XMPP based communication for extended security and ease of scalability.

B. XMPP BASED IEC 61850 COMMUNICATION

Extensible Messaging and Presence Protocol (XMPP) is open based on Extensible Markup Language (XML) [19]. It supports both instant and presence messages. XMPP uses XML as a data exchange format and runs over Transmission Control Protocol (TCP). It offers point to point secure communication by encrypting the data. XMPP clients communicates each other using XML stanzas by connecting to XMPP servers. The small sized XML data units called stanzas [19]. Three kinds of stanzas are supported by XMPP: message, presence and IQ (Info/Query). XMPP nodes are assigned with JIDs (Jabber IDs) when communicating in the network. The communication model is client-server interaction. JID is of the form "client_name@domain_name.com" for XMPP client and "domain_name.com" for XMPP server.



```
No.    Time         Source         Destination    Protocol   Length Info
     7 0.053273     192.168.0.14   192.168.0.15   MMS           245 initiate-RequestPDU
     9 0.116657     192.168.0.15   192.168.0.14   MMS           212 initiate-ResponsePDU
    80 32.847924    192.168.0.14   192.168.0.15   MMS           135 confirmed-RequestPDU
    81 32.865564    192.168.0.15   192.168.0.14   MMS            84 confirmed-ResponsePDU
   231 145.471953   192.168.0.14   192.168.0.15   MMS           135 confirmed-RequestPDU

> Frame 80: 135 bytes on wire (1080 bits), 135 bytes captured (1080 bits) on interface 0
> Ethernet II,          10:da:8b (cc:30:80:10:da:8b), Dst: VaioCorp_11:59:fd (cc:30:80:11:59:fd)
> Internet Prot         , Src: 192.168          192.168.0.15
> Transmission Control Protocol, Src Port:          Port: 102, Seq: 214, Ack: 181, Len: 81
> TPKT, Version: 3, Length: 81
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-RequestPDU
      invokeID: 0
    v confirmedServiceRequest: write (5)
      v write
        v variableAccessSpecificatn: listOfVariable (0)
          v listOfVariable: 1 item
            v listOfVariable item
              v variableSpecification: name (0)
                v name: domain-specific (1)
                  v domain-specific
                      domainId: UPFC_controllerLD0
                      itemId: AVCO1$ST$Vspt$stVal
        v listOfData: 1 item
          v Data: integer (5)
              integer: 1

0000  cc 30 80 11 59 fd cc 30  80 10 da 8b 08 00 45 00   .0..Y..0 ......E.
0010  00 79 4d 47 40 00 80 06  2b ca c0 a8 00 0e c0 a8   .yMG@... +.......
0020  00 0f c9 a9 00 66 b2 63  b0 8e 8e 1f a0 d6 50 18   .....f.c ......P.
0030  00 ff 47 16 00 00 03 00  00 51 02 f0 80 01 00 01   ..G..... .Q......
0040  00 61 44 30 42 02 01 03  a0 3d a0 3b 02 01 00 a5   .aD0B... .=.;....
0050  36 a0 2f 30 2d a0 2b a1  29 1a 12 55 50 46 43 5f   6./0-.+. )..UPFC_
0060  63 6f 6e 74 72 6f 6c 6c  65 72 4c 44 30 1a 13 41   controll erLD0..A
0070  56 43 4f 31 24 53 54 24  56 73 70 74 24 73 74 56   VCO1$ST$ Vspt$stV
0080  61 6c a0 03 85 01 01                               al.....
```

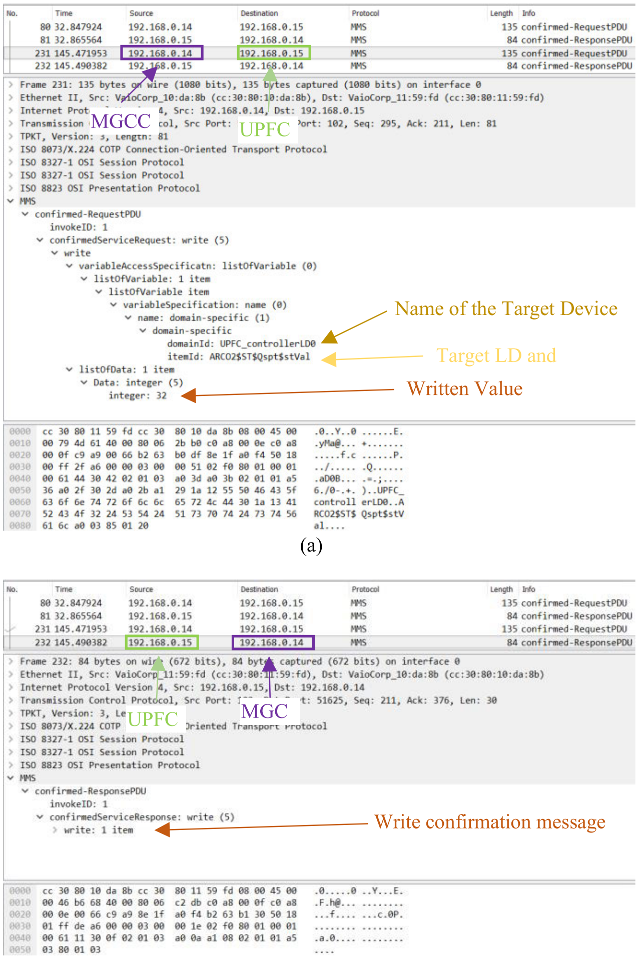
(a)

```
No.    Time         Source         Destination    Protocol   Length Info
     7 0.053273     192.168.0.14   192.168.0.15   MMS           245 initiate-RequestPDU
     9 0.116657     192.168.0.15   192.168.0.14   MMS           212 initiate-ResponsePDU
    80 32.847924    192.168.0.14   192.168.0.15   MMS           135 confirmed-RequestPDU
    81 32.865564    192.168.0.15   192.168.0.14   MMS            84 confirmed-ResponsePDU
   231 145.471953   192.168.0.14   192.168.0.15   MMS           135 confirmed-RequestPDU
   232 145.490382   192.1 .0.15    192.1 .0.14    MMS            84 confirmed-ResponsePDU

> Frame 81: 84 bytes on wire (672 bits), 84 bytes captured (672 bits) on interface 0
> Ethernet II, Src: VaioCorp_11:59:fd (cc:30:80:11:59:fd), Dst: VaioCorp_10:da:8b (cc:30:80:10:da:8b)
> Internet Protocol Version 4, Src: 192.168.0.15, Dst: 192.168.0.14
> Transmission Control Protocol, Src Port: 102, Dst Port: 51625, Seq: 181, Ack: 295, Len: 30
> TPKT, Version: 3, Length: 30
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-ResponsePDU
      invokeID: 0
    v confirmedServiceResponse: write (5)
      > write: 1 item

0000  cc 30 80 10 da 8b cc 30  80 11 59 fd 08 00 45 00   .0.....0 ..Y...E.
0010  00 46 b6 51 40 00 80 06  c2 f2 c0 a8 00 0f c0 a8   .F.Q@... ........
0020  00 0e 00 66 c9 a9 8e 1f  a0 d6 b2 63 b0 df 50 18   ...f.... ...c..P.
0030  02 00 e0 14 00 00 03 00  00 1e 02 f0 80 01 00 01   ........ ........
0040  00 61 11 30 0f 02 01 03  a0 0a a1 08 02 01 00 a5   .a.0.... ........
0050  03 80 01 03                                        ....
```

(b)

FIGURE 8. MGCC sending the voltage reference set point to UPFC_controller (DSTATCOM/Shunt component).

XMPP messages communicates based on XML stanza between IEC 61850 client and IEC 61850 server. Fig. 10 shows the communication between the two nodes say IEC 61850 client and IEC 61850 server using XMPP. The core functionalities are defined by XMPP whereas extended functionalities are defined by XMPP Extended Protocol (XEP) [20]. The XMPP clients exchange the pieces of XML stanzas via the XMPP server of the domain. Initially, a TCP connection will be established between the XMPP server and all the XMPP clients, over which a cryptographic protocol (i.e., TLS) is negotiated between XMPP clients and XMPP server for privacy and data integrity. Over the established TCP and TLS link the XMPP clients and XMPP server will negotiate



```
No.    Time          Source          Destination     Protocol   Length Info
    80 32.847924     192.168.0.14    192.168.0.15    MMS           135 confirmed-RequestPDU
    81 32.865564     192.168.0.15    192.168.0.14    MMS            84 confirmed-ResponsePDU
   231 145.471953    192.168.0.14    192.168.0.15    MMS           135 confirmed-RequestPDU
   232 145.490382    192.168.0.15    192.168.0.14    MMS            84 confirmed-ResponsePDU
> Frame 231: 135 bytes on wire (1080 bits), 135 bytes captured (1080 bits) on interface 0
> Ethernet II, Src: VaioCorp_10:da:8b (cc:30:80:10:da:8b), Dst: VaioCorp_11:59:fd (cc:30:80:11:59:fd)
> Internet Prot          4, Src: 192.168.0.14, Dst: 192.168.0.15
> Transmission           col, Src Port:          Port: 102, Seq: 295, Ack: 211, Len: 81
> TPKT, Version: 3, Length: 81
> ISO 8073/X.224 COTP Connection-Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-RequestPDU
      invokeID: 1
    v confirmedServiceRequest: write (5)
      v write
        v variableAccessSpecificatn: listOfVariable (0)
          v listOfVariable: 1 item
            v listOfVariable item
              v variableSpecification: name (0)
                v name: domain-specific (1)
                  v domain-specific
                      domainId: UPFC_controllerLD0
                      itemId: ARCO2$ST$Qspt$stVal
        v listOfData: 1 item
          v Data: integer (5)
              integer: 32

0000  cc 30 80 11 59 fd cc 30  80 10 da 8b 08 00 45 00   .0..Y..0 ......E.
0010  00 79 4d 61 40 00 80 06  2b b0 c0 a8 00 0e c0 a8   .yMa@... +.......
0020  00 0f c9 a9 00 66 b2 63  b0 df 8e 1f a0 f4 50 18   .....f.c ......P.
0030  00 ff 2f a6 00 00 03 00  00 51 02 f0 80 01 00 01   ../..... .Q......
0040  00 61 44 30 42 02 01 03  a0 3d a0 3b 02 01 01 a5   .aD0B... .=.;....
0050  36 a0 2f 30 2d a0 2b a1  29 1a 12 55 50 46 43 5f   6./0-.+. )..UPFC_
0060  63 6f 6e 74 72 6f 6c 6c  65 72 4c 44 30 1a 13 41   controll erLD0..A
0070  52 43 4f 32 24 53 54 24  51 73 70 74 24 73 74 56   RCO2$ST$ Qspt$stV
0080  61 6c a0 03 85 01 20                               al....
```

(a)

```
No.    Time          Source          Destination     Protocol   Length Info
    80 32.847924     192.168.0.14    192.168.0.15    MMS           135 confirmed-RequestPDU
    81 32.865564     192.168.0.15    192.168.0.14    MMS            84 confirmed-ResponsePDU
   231 145.471953    192.168.0.14    192.168.0.15    MMS           135 confirmed-RequestPDU
   232 145.490382    192.168.0.15    192.168.0.14    MMS            84 confirmed-ResponsePDU
> Frame 232: 84 bytes on wir  (672 bits), 84 byt   captured (672 bits) on interface 0
> Ethernet II, Src: VaioCorp_11:59:fd (cc:30:80:11:59:fd), Dst: VaioCorp_10:da:8b (cc:30:80:10:da:8b)
> Internet Protocol Version 4, Src: 192.168.0.15, Dst: 192.168.0.14
> Transmission Control Protocol, Src Port: 1          t: 51625, Seq: 211, Ack: 376, Len: 30
> TPKT, Version: 3, Le
> ISO 8073/X.224 COTP          Oriented Transport Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8327-1 OSI Session Protocol
> ISO 8823 OSI Presentation Protocol
v MMS
  v confirmed-ResponsePDU
      invokeID: 1
    v confirmedServiceResponse: write (5)
      > write: 1 item

0000  cc 30 80 10 da 8b cc 30  80 11 59 fd 08 00 45 00   .0.....0 ..Y...E.
0010  00 46 b6 68 40 00 80 06  c2 db c0 a8 00 0f c0 a8   .F.h@... ........
0020  00 0e 00 66 c9 a9 8e 1f  a0 f4 b2 63 b1 30 50 18   ...f.... ...c.0P.
0030  01 ff de a6 00 00 03 00  00 1e 02 f0 80 01 00 01   ........ ........
0040  00 61 11 30 0f 02 01 03  a0 0a a1 08 02 01 01 a5   .a.0.... ........
0050  03 80 01 03                                        ....
```

(b)

FIGURE 9. MGCC sending the reactive power set point to UPFC_controller (SSSC/Series component).

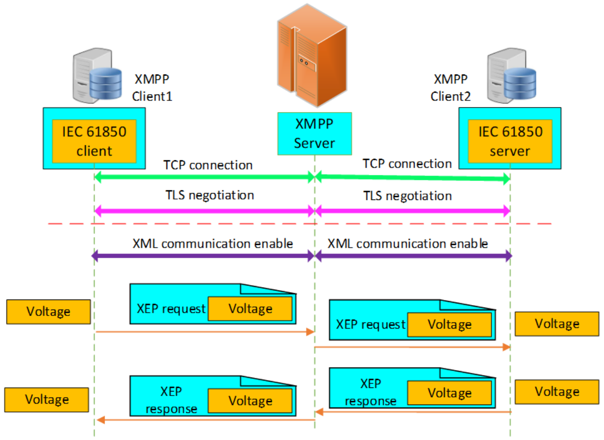


FIGURE 10. Communication among XMPP clients through XMPP server.

a bidirectional XML stream in order to communicate and exchange the XML messages.

The exchange of the XML messages are as follows: IEC 61850 client send a voltage signal message to IEC 61850 server. All the IEC 61850 nodes are hosted by XMPP client module as shown in the Fig. 10. XMPP Client1 module which is hosted by IEC 61850 client node encapsulates the payload into XEP request stanza. The encapsulated stanza is routed to XMPP server. XMPP server routes the information to XMPP client2 node which decapsulates the XEP request stanza. The raw payload signal is received from XMPP client2 module which is hosted by IEC 61850 server. The same encapsulation is performed to transmit payload response message from XMPP client2 node of IEC 61850 server node to XMPP Client1 node of IEC 61850 client through XMPP Server.

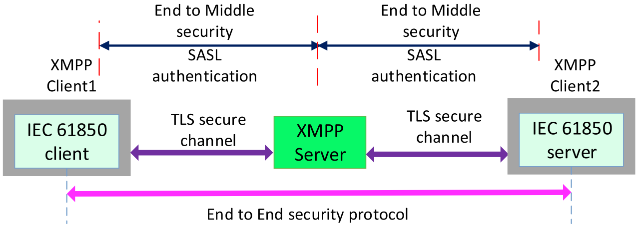


FIGURE 11. XMPP security mechanism.

XMPP provides two levels of security: End to end security and End to Middle security. It also ensures security requirements such as confidentiality, integrity and authentication. End to middle security is related to transport layer established between XMPP client and server nodes, whereas End to end security is related to application layer security established between IEC 61850 client and IEC 61850 server as shown in Fig. 11. TLS negotiation [19] between the nodes ensures authentication of the nodes based on X.509 certificate mechanism. TLS negotiation results in exchange of a secret key among the nodes. Secret key ensures confidentiality and integrity of messages being transmitted. In addition to this Simple Authentication and Security Layer (SASL) ensures authentication between XMPP server and XMPP client. End to end security for IEC 61850 based client and server is ensure by end to end security protocol. This protocol negotiations ensures authentication of end peers.

The IEC 61850 client and servers of different components of microgrid i.e. DERs, UPFC controller, MGCC reside inside the XMPP clients. And all these XMPP clients are connected to an XMPP sever in the microgrid communication network. Figure 12 presents the illustration of IEC 61850 client and servers of different components of microgrids hosted by XMPP clients.

C. MICROGRID POWER MANAGEMENT THROUGH XMPP BASED IEC 61850

IEEE 9-bus system is modified to construct the demonstration system shown in Fig. 13. A solar farm is placed at bus 1 and UPFC is connected between buses 1 and 4. Two additional DERs have been placed at buses 5 and 9. Bus 7 serves at the point of coupling to the utility grid. Needless to say, the microgrid can operated in islanded mode as well. The

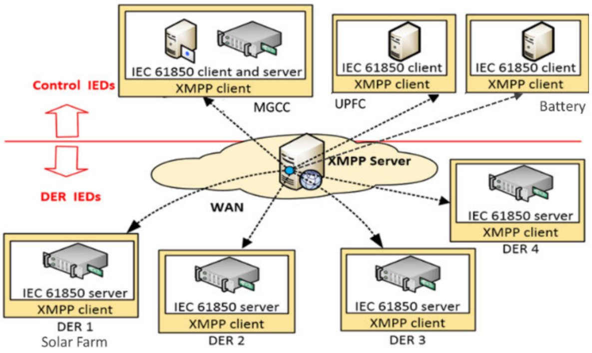


FIGURE 12. XMPP communication network for the IEC 61850 based IEDs in microgrid.

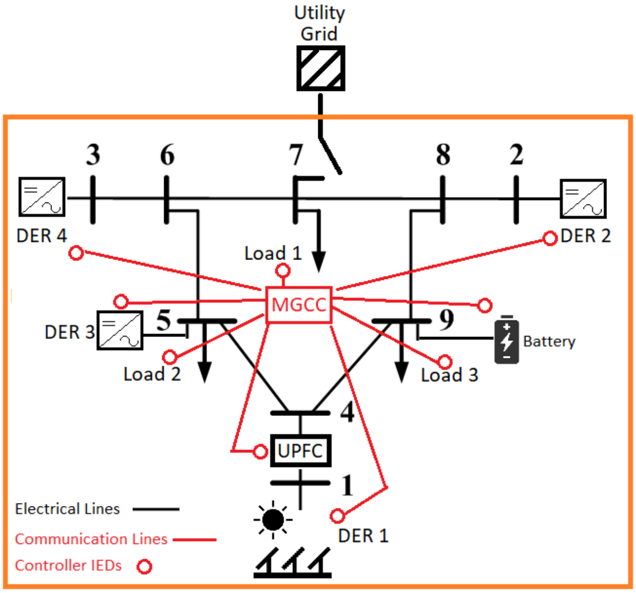


FIGURE 13. Modified IEEE 9-bus system used as a microgrid test system.

microgrid is connected to the utility grid at PCC through a CB. All DERs as well as UPFC have a controller IED, which are connected to MGCC.

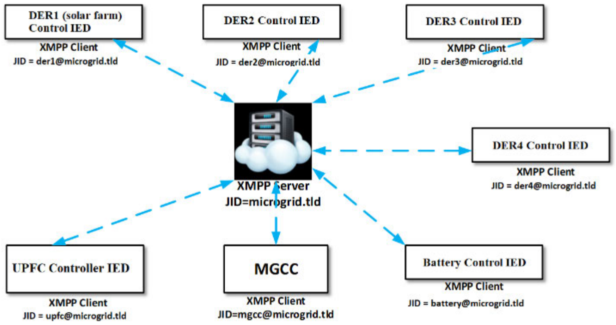


FIGURE 14. IEC 61850 based XMPP communication network of the microgrid.

The IEC 61850 based XMPP communication network of test microgrid is as shown in Fig. 14. The DER control IEDs, UPFC controller IED and MGCC are hosted by XMPP clients, with unique JID address ‘der1@microgrid.tld’, ‘upfc@micorgrid.tld’, ‘mgcc@microgrid.tld’ etc. These XMPP clients are connected to a WAN to which has a XMPP server of with JID ‘microgrid.tld’ is the same domain. The XMPP clients i.e IEDs may exchange information among themselves via the XMPP sever, which acts a router, over the WAN.

Initially, all the DERs update their status to the MGCC. MGCC builds the status vector [S], based on this data. The XMPP communication flow is given as

DER1 control IED_DPST1 \$ ST \$ ECPConn \$ stVal→ *der1@microgrid.com* → *microgrid.com* → *mgcc@microgrid.com* → MGCC

The MGCC also fetches current active and reactive power outputs of all the DERs, as per the communication flow shown below,

DER1 control IED_MMXU1 \$ TotW \$ MV→ *der1@microgrid.com* → *microgrid.com* → *mgcc@microgrid.com* → MGCC

DER1 control IED_MMXU1 \$ TotVAr \$ MV→ *der1@microgrid.com* → *microgrid.com* → *mgcc@microgrid.com* → MGCC

Based on this information, the MGCC calculates the voltage reference point, active and reactive power set points for UPFC controller. The voltage reference point (v_{ref}) for DSTATCOM part of UPFC controller is communicated to DO ‘Vspt’ of logical node AVCO of UPFC controller by the following XMPP communication flow as follows

MGCC→*mgcc@microgrid.com*→*microgrid.com* → *dstatcom@microgrid.com*→UPFC controller IED_AVCO \$ SP \$ Vspt \$ setMag

Similarly, active and reactive power reference points (P_{ref}, Q_{ref}) for SSSC part of UPFC controller are communicated to DOs ‘Pspt’ and ‘Qspt’ of logical nodes AACO and ARCO respectively. The XMPP communication flow is as follows

MGCC→*mgcc@microgrid.com*→*microgrid.com* → *dstatcom@microgrid.com*→UPFC controller IED_ARCO2 \$ SP \$ Pspt \$ setMag

MGCC→*mgcc@microgrid.com*→*microgrid.com* → *dstatcom@microgrid.com*→UPFC controller IED_AACO \$ SP \$ Qspt \$ setMag

V. CONCLUSION

UPFC controllers have the potential to be influential in microgrid control solutions. Such solutions require an information model for UPFC to be smoothly integrated. In order to fill this gap, this paper develops an IEC 61850 information model for a UPFC controller. In order to validate the model and showcase its use, a microgrid control system with UPFC, battery and DERs is developed. All the components as well as the control strategy are mapped to IEC 61850 models and message exchanges. Lab tests are performed to validate the models and successful message exchanges. As the next step, the overall system is extended to XMPP-based communication. XMPP protocol is utilized in microgrids communication for scalability and additional security. The IEC 61850 message exchanges over XMPP for coordinated control and power management are demonstrated. Future-work, may focus on using additional cybersecurity solutions to mitigate other vulnerabilities.

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