Power Line Communication from Home Automation to Solar Farm Monitoring

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Power Line Communication (PLC)

- Since 1988
- Utilize existing AC power lines to carry high freq data signal
- Data rate from 1Kbps – 200Mbps
PLC signal on AC 220V

622V

0.4V

80kHz
Voltage (Parallel) Mode PLC

Device = Appliance, Computer, ADSL, etc

PLM = Power Line communication Module
PLM 80-90kHz

Data

DSP

Tx

Rx

10μF
100Ω
15nF
470μF
6.8μH
220V_{ac}
470nF

64Kbps, OFDM
# PLC classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Narrow Band</th>
<th>Broad Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.</td>
<td>3-500kHz</td>
<td>2-25MHz</td>
</tr>
<tr>
<td>Data</td>
<td>2-128Kbps</td>
<td>10-200Mbps</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; km</td>
<td>&lt; 300m</td>
</tr>
<tr>
<td>Uses</td>
<td>Monitor/Control</td>
<td>High Speed Data</td>
</tr>
<tr>
<td>STD</td>
<td>PRIME,G3,X10</td>
<td>Home Plug Av</td>
</tr>
<tr>
<td>App</td>
<td>Smart Grid</td>
<td>Home Network</td>
</tr>
</tbody>
</table>
Home Automation (narrow band < 500kHz)

X10, LonTalk

www.sentec.com
Home Area Network  Broadband <25MHz
High speed <200Mbps

Home Plug
Home Plug AV
Street Lighting

Lamp maintenance & dimming

Long range

www.smartlighting.com
EV Charging station

www.greenvity.com
Smart Grid
Narrow band, Long range

MDM
OM
DSM
etc

PRIME, G3
Problems with PLC

1) Noises
   1.1) Motor & Switch (intermittent)
   1.2) Switching Power Supply
       (Periodic impulse)

2) Unknown Topology
   2.1) Line characteristic varies
   2.2) Frequency & Time dependent
   2.3) Multiple reflection (coupling loss)
Smart Grid Technology
low data rate (32kbps), real time, long range
PowerLine Intelligent Metering Evolution

Open International PLC Standard for Advance Metering, Grid Control and Asset Monitoring applications

2,500,000 meters deployed worldwide
PRIME Tree Topology

BN: Base Node (DCU)
SW: Switch Node (Meter)
SN: Service Node (Meter)
Smart Meter

220V AC in

PLC (PRIME)

220V AC out

RF (Zigbee)
Advance Metering Infrastructure (AMI)

Data Concentrature (BN)

PLC

RF, Optic

Internet

Corporate Utility Network

SN

SW

SN

SW

SN
PRIME Protocol Layer

DLMS - COSEM
IEC61334-4-32
IPv4 / IPv6
DFU
RMI

CONVERGENCE SUB-LAYER
MAC LAYER
PHY LAYER

PL medium

41.992KHz – 88.867KHz  128 Kb/Sec  OFDM
PRIME OFDM

- The first sub-channel is used as reference: Pilot sub-carrier
- Other sub-channels carry a Differential Phase Shifting Key Modulated Symbol
  - Each modulation symbol carries a number of data bits based on the PSK mode

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Bits/carriers</th>
<th>Total</th>
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<tbody>
<tr>
<td>DBPSK</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>DQPSK</td>
<td>2</td>
<td>192</td>
</tr>
<tr>
<td>D8PSK</td>
<td>3</td>
<td>288</td>
</tr>
</tbody>
</table>

CENELEC BANDS

- 96 DxPSK modulated subcarriers plus one pilot
- 47 kHz Bandwidth (from 42 kHz to 89 kHz)
- 95 kHz
- 125 kHz
PRIME MAC Frame Structure

- **Beacon Period**: transmit a well defined messages used for network synchronization
- **SCP Period**: Shared Contention period used to transmit data and control packet
- **CFP Period**: Contention Free Period used to transmit data without collision (Optional)

276 OFDM Symbols = ~618 ms
Solar Farm Monitor

8MW  86668 PV panels: fixed topology

20-100V
50-200W
## World Bank 2012 Renew energy projects

<table>
<thead>
<tr>
<th></th>
<th>Global (MW)</th>
<th>Thailand (MW)</th>
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</thead>
<tbody>
<tr>
<td>Bio</td>
<td>1277</td>
<td>39</td>
</tr>
<tr>
<td>Hydro</td>
<td>31060</td>
<td>0</td>
</tr>
<tr>
<td>Wind</td>
<td>28900</td>
<td>127</td>
</tr>
<tr>
<td>Solar</td>
<td>7695</td>
<td>326</td>
</tr>
</tbody>
</table>
Blackout
22 May 2013

Lightning strike on 500KV

Not enough local Power generation
PV’s are not identical but must operate at the same current → un-optimal
Mismatched PV panels
defect, cloud, trees, airplane, direction
crack, dust, leaves, aging, temperature
Effect of Mismatched PVs

$P_1 + P_2 < P_{1m} + P_{2m}$ 20% loss
Solar Farm (Health) Monitoring

MU : Monitor Unit (V,I,Temp)
CU : Communication Unit
DCU: Data Concentrator Unit

Control center

AC
DC

MU CU
MU CU
MU CU
MU CU
RF 433MHz or 2.4GHz

Expensive, Fragile & Complicate
Serial Mode PLC
AC Current Mode PLC (analog tech)

Low cost: uses current transformer for coupling high frequency current signal
Pulse PLC (digital tech)

Low cost. Toggle switch to transmit data
1) AC Current Mode PLC

Superimpose AC Current onto DC Current

\[ \text{PV & INV must be short circuit at carrier frequency } \omega_0 \]
PLC Current Coupling Circuit

\[ V_i \quad \rightarrow \quad I_{ac} \quad \rightarrow \quad I_{ac} \quad \rightarrow \quad V_o \]

\[ L_m, L_k \]

\[ C_2 \quad L_1 \quad C_1 \]

Rx

Tx

Vi

Vo
Tx Mode

\[ Z_o = \infty \] to couple current

\[
\omega_0^2 = \frac{1}{(L_1 \parallel (L_m + L_k))C_2}
\]

\[
\omega_0 = \frac{1}{\sqrt{(L_1 \parallel L_m)C_2}}
\]

\[
i_i = j\omega C_2 V_i
\]
Rx Mode

\[ Z_i = 0 \text{ to avoid loading DC line} \]

\[
\omega_o = \frac{1}{\sqrt{L_1 C_1}}; \quad V_o = \frac{-j I_{ac}}{\omega_o C_1} = \frac{C_2}{C_1} V_i
\]

\[
\omega_o^2 = \frac{1}{(L_1 + L_k) C_1} \cdot \frac{1 - \omega_o^2 L_k C_2}{1 - \omega_o^2 (L_1 \parallel L_k) C_2}
\]
50W Amorphous PV panels
Carrier frequency

\[ Z_{PV} \]

\[ 3\Omega \]

\[ 0.81A \]

\[ 980 \]

\[ 2.2 \]

\[ 0.8\mu \]

\[ 250kHz \]

\[ \omega_0 \]

\[ I_{Load} = 0.46 \, A \]

\[ I_{Load} = 0 \]
Test Experiment for simulation

L_m = 84 \mu \text{L}
L_k = 36 \mu \text{L}
R_s = 50
R_L = 10k

L_1 = 220 \mu \text{H} ; \ C_1 = 5.22 \text{nF}
C_2 = 1.39 \text{nF} ; \ R_s = 50
R_L = 10K ;
V_i = 1V_{ac} ; \ I_{ac} = 2.18mA_{ac}
Energy loss per PV = 14 \mu \text{W}
Monte Carlo Simulation

50 simulations, 20% over 3 sigma

Gaussian Distribution

\[ \frac{V_o}{V_i} \]

frequency (kHz)

\( f_0 \)

250kHz
Amplitude Shift Keying (ASK)

Data Rate = 25kbit/sec
MU & CU Circuit

Consume 50uA (2.5mW) while idle
Low Power MU & CU Circuit

M1 is on to wake up MCU
MCU turns on/off M2 to keep power on/off to save power
Low Power Communication Protocol

CU

wake (111)

addr & instr

ack

response

sleep

DCU
A switch closes temporarily to create a pulse that propagates through the DC Power Line.

\[ V_D = (n - 1)V \]  if one PV switch closes

\[ V = 0 \]  for all PV  if DCU switch closes

Thus DCU can broadcast data to all PVs
PV can reply to DCU only
Ideal Waveforms: 8 x (50V) PV

$V_{DCU} \rightarrow PV$

$V_{PV} \rightarrow DCU$

$400V \rightarrow 8\mu \rightarrow 50V \rightarrow 300\mu \rightarrow 600\mu \rightarrow 0$
Pulse shaping due to PV Capacitor

- $C = 65\text{nF}$
- $V_{pv} = 50\text{V}$
- $I_{ph} = 0.015 \rightarrow 0.5\text{A}$

$T_r = 6.5 \rightarrow 220\mu\text{S}$

Data Rate

$$T_r < \frac{1}{8\mu + T_r} = 4.4\text{kHz}$$
Ringing due to transmission line effect

\[
L = 1.475 \mu \text{H/m}, \quad C = 11.3 \text{pF/m}
\]

cause ringing

\[ +V_{\text{DCU}} \]
Ringing through DC Line \( R = 10 \); \( L = \); \( C \)

Pulse (V) across PV1

Pulse (V) on DCU

- 15m cable
- 35m cable
- 1.8MHz
Ringing Suppression at DCU

\[ R_Y = 410 \Omega \text{ to match } Z_0 \]
\[ C_Y = 2 \text{nF to block DC} \]
Ringing Suppression at the Switch

Hard Switch

Soft Switch

$V_{pv}$
50W Amorphous PV panels
a) Hard Switch (IRFS630)
b) Terminate DCU with 410 + 2.2nF
c) Soft Switch with 1.5K & 150pF
d) Soft Switch under weak sunlight
Negative edge detector

Q is OFF when idle (zero power)
ON when there is a neg. pulse

PV panel

DC line

μC

ON/OFF Switch

in

out

TP

V_{PV}

C_1

R_1

Q

R_2

C_2
Design Eq.

\[ \Delta_P = \frac{C_1}{C_1 + C_2} \Delta_{PV} \; ; \; \Delta \approx \frac{R_2}{R_1 + R_2} \Delta_P \leq 0.7 \]

\[ T_P = (R_2 + R_2)(C_1 + C_2)\ln\left(\frac{\Delta}{0.7}\right) \]

\[ R_1 = R_2 = 10\text{K\Omega}; \; C_1 = 470\text{pF}; \; C_2 = 4.7\text{nF}; \; \Delta_{PV} = 80V \]

\[ \Delta_P = 7.27V; \; \Delta = 3.63V; \; T_P = 170\mu\text{S} \]
Experimental Result

Voltage across DCU (100V/div)

- Strong
- Weak

Broadcast by DCU

One MU responses
Edge Detector with Regulator

PV panel

DC line

40V

3V

C1

R1

C2

R2

Q

MCU
Edge Detector with Regulator

PV panel

DC line

40V

3V

R1, R2

C1, C2

Q

MCU

3V

3V
$T_P$ is long to allow MCU to turn on $Q_3$ and keep $V_{DC}$ supply to MCU.

MCU turns off $S$ to shut down (All transistors OFF)
Effect of Mismatched PVs

\[ P_1 + P_2 < P_{1m} + P_{2m} \]

20% loss
Future Work: Integrated Converter

DC/DC maximizes energy
a) from PV.

b) to DC/AC.

Communication Unit (CU) shares information.
Advantages of using PLC for solar farm

1) No extra wire
2) Simple Circuits → low cost
3) Low power
4) Fixed topology
5) Low noise
6) Low power protocol
Thank You

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