Smart grid challenges and signal processing based solutions - A Literature survey

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Abstract

Smart grid is a power grid which allows bidirectional power flow along with information interchange between supplier and user. It promises power can be more efficiently and reliably generated, transmitted and consumed over conventional electricity systems. To establish the above grid system the conventional grid system should be upgraded with new technologies. This paper presented the techniques to meet the smart grid requirements and also spells the challenges while deploying the advancements. More over the increases of distributed generators (solar, wind etc.) need integration with smart grid for the purpose of managing peak load. In this article some of the smart grid challenges and the solutions in signal processing perspective are presented.

Key words: EMS, Harmonics, Islanding, Peak load, PLC, PMU, Rapid charging, State estimation.

I. INTRODUCTION

This is an important period to modify the present power grid, because we need to apply new technologies to produce, distribute, deliver and use electricity efficiently. The present grid systems are based on, a one way flow of energy and information from the source to the end user. But in future due to the increase of distributed generators (wind, solar, other renewable energy sources) and to use the electric power efficiently we need two way flows of energy and information throughout the system. The above requirement is provided by the grid system called smart grid. Traditional electric power grid and smart grid conceptual model is shown in figure 1 and 2 respectively.

![Diagram of traditional electric power grid](image)

Fig.1. Traditional electric power grid

The signal processing tools are developed to deal with the smart grid developments because signal processing includes the monitoring, measurement and processing sequences from acquisition, analysis, detection, extraction and classification of the waveforms [2] which may carry useful information for identification of system events and load characteristics. In this scenario signal processing meets the different challenges, among which few challenges with possible solutions are articulated in this paper. The efficiency and reliability of power delivery will be improved by intelligent monitoring and controlling of energy flow in power grid. This monitoring is enabled by two way communication links and this leads to introduction of noise in the system. And also while smart grid enables power grid network there is an increase in risk of cyber attacks because of strong dependence on the cyber infrastructure in the system.

Demand response management is another challenging task on the smart grid which forecast the load/price and it reduce the consumption of power during the peak load. Observing the power grid is essential for a more intelligent, efficient and reliable smart grid with increasing user visibility. Signal processing techniques and inexpensive equipment could enable to observe local power grid. And finally Smart infrastructure is required to integrate plug in electric vehicles into the smart grid which involves number of signal processing techniques. The observation emphasise that the existing power distribution is not in the position to predict the increase in load caused by charging of Electric Vehicles (EVs) batteries. The discussions on the above challenges and possible solutions are presented in the next sections.

II. POWER LINE COMMUNICATION (PLC) ON POWER GRID

The intelligent monitoring and energy flow control [6] in future smart grid requires low-delay, highly reliable communication between customers local utilities and regional utilities. The possible solution for the above requirement is the deployment of two way flow of energy and information. To enable bidirectional flow of information [3] PLC systems have been developed for the every part of the grid.

2.1. PLC systems classified in three bandwidth categories

(i) Ultra narrowband (UNB or very low frequency (VLF) PLC systems

This system operates in the range 0.3 – 3.0khz band to provide 100 bits/sec over the range of 150km. This system has the application in automatic meter reading, outage detection and voltage monitoring.

(ii) Narrow band (NB) or low frequency (LF) PLC systems

This system operates at 3-500khz band to deliver a few kilobits per second
(iii) Broad band (BB) or high frequency (HF) PLC systems
This system operates in the range of 1.8 to 250MHz to provide up to 200Mbits/sec for home area network (HAN). For local utility applications narrowband PLC systems are used. The major challenge in this system is overcoming channel distortion and noise.

2.3. Channel Models
In PLC systems the electric grid constitutes the transmission medium. The signal propagates through electric wires and various discrete components such as transformers. The PLC system channels are modelled in two ways. (i) Multipath Modelling and (ii) Transmission line (TL) modelling. In multipath modelling the channel is viewed as unknown quantity, so that the channel parameters are determined by the suitable training algorithm to determine unknown quantity. On the other side the transmission line modelling the channel is viewed as deterministic model so that TL theory involved estimating the parameters. Network analyzers are used to measure parameters of various components such as transformers and capacitor banks. The channel has the time varying behaviour based on the device connected to the power line network. If the devices dominate the system impedance the channel will exhibits a time varying behaviour.

2.4. Noise Models
Power line noise is a significant factor in NB-PLC system. Typical sources of PLC noise include switching power supplies, SCRs, dimmer switches etc. The switching noise is non-white with time varying spectral content that exhibits a 1/f type decay due to the decreasing concentration of noise sources with frequency and the used semiconductor devices. The PLC noise has three components (i) Generalized background noise (ii) Periodic noise and (iii) asynchronous impulsive noise. Interference from uncoordinated devices leads to significant reductions in data rates and affect overall reliability. These uncoordinated systems would be treated as noise at the receiver. In addition to uncoordinated PLC devices, there is inference from other uncoordinated man-made technologies such as broadcast stations over medium and short wave broadcast bands.
In non Gaussian noise environments, the SNR loss of DPSK increases over 3db as the noise becomes more impulsive. This is because the occurrences of high amplitude impulse noise. In highly impulsive noise environments the decrease of sub channel SNR can be too severe to be mitigated by forward error correction.[3] In this situation filtering algorithms can be used to remove the impulsive noise from the received signal before passing it to the detector.

2.5. Deployment challenges

The dominating PLC technology is based on deployment environment, regulations and the specific applications. In rural deployment the number of households per meter on the LV side of the MV/LV transformer will typically small. So that it is economical to have a concentrator on the LV side of the transformer and also if the distance of reaching house hold meter is too long (tens of kms) then the PLC technology with 50-500 kHz is challenging.[3] Based on the distance and the number of meters per square km area per transformer the PLC standard was selected. The current standards of PLC technology are PRIME,G3, G.HNEM and IEEE1901.2 and TNACS etc[6]. All the above models and PLC deployment needs an advanced signal processing techniques.

III. DETECTION OF DATA INJECTION ATTACK

The impact of data injection attack is more during state estimation process. The main function of state estimation is to estimate, through processing the set of real time redundant measurements, the electrical states of power systems, typically bus voltage magnitude and phase angles. State estimation is a key function in building a real time network model in the energy management systems (EMS).Bad data processing is one of the main task in state estimation this means that identify and eliminate the measurement errors and bad data [1] injections.

3.1. System model for state estimation

To simplify the system analysis we use direct current power flow model

\[ Z = Hx + e \]

Where \( H \in \mathbb{R}^{M \times N} \) DC power flow matrix

\( Z \in \mathbb{R}^{M} \) –Measurement signal vector

\( X \in \mathbb{R}^{S} \) – System state vector

\( e \in \mathbb{R}^{M} \) – Measurement noise vector

\( \Sigma_e \) –Covariance matrix of ‘e’

3.2. Bad data injection and detection

Cyber data injection attacks can be modelled as

\[ Z = Hx + C + e \]

Where ‘C’ is the bad data injected by the attacker.

The attack could be launched by one single attacker or by a group of coordinated attackers. [1]The objective of defender (system operator) is to reliably detect an injection attack in the event of an attack.

Let \( H_0 \) representing the no-attack hypothesis and \( H_1 \) representing the attack hypothesis therefore \( H_0 : C = 0 \) ;\( H_1 : C \neq 0 \). We denote the true hypothesis and the decision of the detector by \( T \in \{ H_0 : H_1 \} \) and \( D \in \{ H_0 : H_1 \} \) respectively. Therefore the probabilities of misdetection and false alarm are given by \( P_{fa} = P \{ D = H_0 | T = H_1 \} \) and \( P_{fa} = P \{ D = H_1 | T = H_0 \} \). If the attacker has knowledge on \( H_1 \) it can add \( C = Hb \) as a result we have \( Z = H(x+b) + e \) such that the control centre believes that the true state is \( x + b \) . This is called stealth bad data injection.

The advanced detection approaches and mitigation of this issue are:

i). Adopting stealth bad data injection.

ii). Deploying advanced measurement units such as PMUS at various locations to reduce the chance of data injection attacks.

3.3. Bad data detection at control centre

Bad data in the state estimate is caused by two possible sources (i) nature (ii) man-made data injection. The man-made data injection is considered as bad data injection in the system. Bad data injection techniques detect the abnormalities in the state vector estimates. Given that the measured power flow \( Z \) and the estimated state vector \( \hat{X} \) can be computed as

\[ \hat{X} = (H^T \sum_{e}^{-1} H)^{-1} H^T \sum_{e}^{-1} Z \]

The residue vector ‘r’ can be computed as the difference between the measured quantity and the calculated value from the estimated state

\[ r = Z - H \hat{X} \]

The expected value and the covariance of the residual are \( E(r) = 0 \) and

\[ \text{cov}(r) = [1-H(H^T \sum_{e}^{-1} H)^{-1} H^T \sum_{e}^{-1}] \sum_{e}^{-1} \]

The bad data due to faulty sensors and topological errors can be performed using a threshold test over ‘r’ in which the normal static hypothesis is accepted if \( \max|r| \leq \gamma \). Where ‘\( \gamma \)’ is the threshold, ‘\( r_i \)’ is the component of ‘r’ otherwise the abnormal state hypothesis is accepted.

IV. DEMAND RESPONSE MANAGEMENT AND PRICE FORECASTING

The inefficiency of power grid at peak demand can be mitigated by introducing the concept of Demand
Response (DR). DR is the mechanisms used to encourage consumers to reduce demand during peak hours, thereby reducing the peak electricity load. Present DR schemes are implemented with commercial as well as residential customer who is either incentive based or time based rates DR schemes.

4.1. Application of signal processing Techniques

In order to meet the promises of the smart grid, a wide range of communications electronics and other related technologies have to be deployed at various levels of the grid. Automatic sensors such as phase measurement units (PMUs) will increasingly be deployed at both T&D levels. These units allow real time (RT) synchronous measurements of voltages and currents at transmission lines and distribution stations.

Communication technologies are required to transmit reliably data and control information across the grid for proper operation. This large amount of information exchange between the users and suppliers also calls for an efficient compression method and secure transmission schemes. On the user side low cost and low power automated home Energy Management Scheme (EMS) with networked smart electric appliances possessing DR capability also need to be developed. An important signal processing application to the smart grid is advanced communication technology to facilitate information exchange between smart devices.

PLC technology is gaining popularity for its low deployment cost and network latency. It exploits the existing power grid so that the deployment cost can be greatly reduced. Network latency and security can be directly controlled because the communication channel is owned by the utility. The recent reviews shows that the PLC can be applied to different components at the smart grid from high voltage lines to smart meters and within the home [15].

The large amount of information exchange is possible because of these advanced transmission schemes. This requires efficient signal processing algorithm to analyze the information so that decisions can be made by the home EMS in a short time of interval to provide the control of appliances and achieve better DR on the customer side. The Demand response management optimization in a smart home through the home energy management scheme (EMS) is shown in figure 4.

Fig.4. Smart home through home EMS

Smart grid has the capability to self-healing, Flexible, predictive, interactive, optimized and secure. To be able to predict the behaviour of the grid and customer an appropriate model is needed to estimate the corresponding parameters from measurements. This is related with machine learning, event detection and time series analysis. Time series analysis is one of the parameter estimation techniques. For state space estimation kalman [5] filter gives better result.

Most of the electric appliances such as ACs, heaters and ventilating units are described by differential equation involving device specific as well as environment parameters. In digital domain its evolution behaviours can therefore be described by the discrete-time nonlinear state space models.

For a nonlinear state space model state equation:

\[ x_k = h(x_{k-1}, u_k) + w_k \]

Measurement equation:

\[ z_k = g(x_k, u_k) + v_k \]

Where \( x_k \) - state vector
\( u_k \) - input vector
\( z_k \) - observation vector at the kth time instant of dynamical system.
\( w_k \) - Probability density function

For linear state space model state equation:

\[ x_k = A_k x_{k-1} + B_k u_k + w_k \]

Measurement equation:

\[ z_k = C_k x_k + D_k u_k + v_k \]

Where \( A_k \) - State transition matrix
\( B_k \) - control input matrix
\( C_k \) & \( D_k \) - observation model
\( v_k \) - Measurement noise

The number of prediction algorithm were developed based on kalman filter predict
\[ \hat{x}_{k|k-1} = A_k \hat{x}_{k-1|k-1} \]
\[ p_{k|k-1} = A_k p_{k-1|k-1} A_k^T + Q_k \]
Update \[ \hat{x}_{k|k} = \hat{x}_{k|k-1} + k_k (z_k - C_k \hat{x}_{k|k-1}) \]
\[ p_{k|k} = (I - k_k C_k) p_{k|k-1} \]
\[ k_k = p_{k|k}^{-1} [C_k p_{k|k}^{-1} C_k^T + R_k]^{-1} \]

Where \( Q_k \& P_k \) are covariance of \( v_k \& w_k \) respectively. The subscripts \( \hat{x}_{k|k-1} \& \hat{x}_{k|k} \) are used to denote quantities after prediction and update.

4.2. Forecasting technique for electricity price and load

DR is effective if the grid system has the ability of load/renewable energies forecasting at the utilities side and price forecasting at the market as well as customer side. Real time price (RTP) forecasting has to be done in the much shorter interval. The RTP [5] is based in DR i.e interaction between demand and the price of electricity with consideration of renewable energy. This RTP forecasting requires the tool which has to forecast the price based on the time and period of consumption. Algorithms like [11] ANN, SVMs and FPCA gives better solutions on DR based price forecasting.

V. SMART INFRASTRUCTURE FOR PLUG IN ELECTRIC VEHICLES (EVs)

Increase in usage of electric vehicles concern about reducing carbon emission leads a proper energy management which requires smart distribution grid infrastructure [12]. The present grid structure is not capable to predict the increase in load caused by charging of the EVs batteries, this requires the emerging signal processing techniques to manage EVs connected to smart grid. The vehicles that are exclusively powered by onboard batteries are called plug in electric vehicles (PEVs) and those with an additional internal combustion engine are called plug in hybrid electric vehicles (PHEVs). Naturally PEVs are equipped with larger battery capacity than PHEVs.

During the period of charging the batteries it consumes much power approximately it doubles the power when compared with home consumption. This increase the load on distribution transformer causes the voltage drop (swell) at the time of charging. The possible solution for this is change the EVs at night when the home load is at its minimum. Still it requires control information regarding when to charge an electric car. This issue is rectified by enabling the conventional power grid embedded by communication and control mechanism. The role of signal processing is to predict the impact on the grid and also to manage the power quality issues. The quality of electric energy delivery improved by utilizing smart metering technology [14], if the difference between the nominal voltage and supplied voltage i.e voltage drop is seen as an error signal there is an algorithm developed to minimise noise or estimation errors.

Another important factor we need to consider while designing of EV charging algorithm is electric grid stability. When EVs on the grid because the batteries equivalent models are resistive, inductive and capacitive (RLC) circuits. EVs not only act as a load to grid and it serve as a source for local electrical power by discharging their batteries into the grid in V2G application. In this application signal processing algorithm may be used to control both real and reactive power injected back into the grid. The schematic structure of EVs charging at home and at charging station is as shown in figure 5.

![Fig.5. Structure for Electric vehicles charging system](http://www.ijettjournal.org)
energy storage systems to reduce the loading of power grid.

Here the signal processing techniques are used to predict the expected demand on the charging station so that enough energy is locally stored in advance [7]. The charging demand estimated with the help of traffic information. This requires the integration of smart grid and intelligent transportation systems which leads to unified smart infrastructure system. This will be accomplished through vehicles to vehicle and vehicle to infrastructure communication. This area meets number of signal processing problems especially when designing the communication process. The above technique not only helps the design of energy distribution and storage systems but also use to scheduling the charging of the station storage system which avoids the damage of distribution grid during peak load and also helps to integrate renewable energy sources.

VI. POWER GRID MONITORING

The promise and goal of a smart grid is to enable a more intelligent, efficient and reliable power grid with increasing user visibility and participation. Collecting the power grid parameters (frequency, voltage, and phase) at anywhere and at any time provides the information about the operational characteristics, event occurrence and power quality issues etc[9][6]. Technology has progressed that it is possible for anyone to monitor the grid efficiently and cheaply. Signal processing techniques and inexpensive equipment could enable researchers to observe local power grids. The additional visibility would promote new insights and improved understanding toward a more reliable efficient power grid.

Voltage at various points on the power grid are described by voltage phases $V_i \angle \theta_i$, where $V_i$ is the magnitude of the voltage and $\theta_i$ is the phase of the voltage at bus ‘i’. The power flow through a transmission line is a function of the impedance of the transmission line ‘X’. The voltage at the end of the line are $V_j \angle \theta_j$ then

$$P_j = \frac{X}{|Z|^2} V_i V_j \sin(\theta_i - \theta_j)$$

if losses are included then the equation becomes

$$P_j = \frac{X}{|Z|^2} V_i V_j \sin(\theta_i - \theta_j) + \frac{R}{|Z|^2} \left[ \frac{X}{|Z|^2} V_i^2 - V_i V_j \cos(\theta_i - \theta_j) \right]$$

In these equations $Z=R+jX$ where ‘R’ is the loss term. Power generally flows from areas of leading phase to area of lagging phase.

6.1. Power theft detection

Non Technical Losses (NTL) in the electrical power system is the transmission and distribution losses originating from Electrical theft and other illegal use of electricity. These losses however differ from Technical losses as these cannot be detected or measured accurately. The NTL comprises of illegal connections, meter tampering, billing errors etc. out of which electricity theft through meter tampering and direct rigging from the transmission or the distribution line contributes higher percentage of loss of electricity. Theft of electricity in the world is one among the major loss of revenue irrespective of being a developed or a developing nation. In United States of America, the NTL are estimated to about 0.5% to 3.5% of the gross annual revenue. In developing countries like India, the loss of electricity due to theft is projected to about 20% to 30% of the overall loss in Power utility.

The system [6] to detect and monitor the theft of electricity using the principle of Power Line communication (PLC). As in PLC, a narrow band power line carrier signal of higher frequency can be transmitted in the power line along with the power frequency signal. The variation in the amplitude of this carrier signal can be monitored at regular intervals and the theft of electricity can be detected by the computation of the differential change in the amplitude of the carrier signal.

6.2. Load frequency monitoring and control

If the generation $P_G$ is not matched to the load $P_L$, the generators slow down converting some of the kinetic energy from spinning motion into electric energy, The rate at which this occurs is dependent on the inertia of the system. The energy balance in a equation form is given as:

$$P_L = P_G + \frac{2H}{f_0} \frac{df_D}{dt} + \beta f_D,$$

Where ‘$f$’ is the frequency response of the system encompassing changes in generation with respect to frequency. $f_D$ is the frequency deviation. The change in power versus frequency is known as the regulation ‘R’ of the generator.
To maintain the frequency around a specific value 50 or 60Hz, the secondary control system is necessary. The control is accomplished via a signal known as the area control error (ACE). It is computed for each area by measuring the difference between actual power transmission \( T_a \) and scheduled transmission \( T_s \) and \( f_D \) is the deviation of frequency from its scheduled value.

\[
ACE=(T_a-T_s)-10Bf_D
\]

\( B \) – Constant (frequency response of the system specified in units if MW/0.1Hz)

The ACE act as a control signal for adjusting \( P_{ref} \) (the nominal generator output)

\[
P_{ref}(t) = K_pACE(t) + K_i \int_0^t ACE(x)dx
\]

6.3. Voltage waveform monitoring

The primary interaction of most users with the power grid is the common wall outlet. The outlet is the power source which accepts the plug from innumerable devices. The basic voltage waveform is commonly known sine wave 230V, 50Hz.

(i) Harmonics: The waveform becomes more complex due to the presence of harmonics of the fundamental signal. These extraneous signals come from the various nonlinear devices on the system that feed back some energy into the system. Harmonics are produced by nonlinear loads such as switching DC power supplies, new technologies such as plug in electric vehicles and wind generation have the ability to create additional harmonics on the grid that need to be monitored or reduced.

The impact of harmonics is felt through reduced power quality and reduced equipment life span. Beyond the basic harmonics additional signals called inter harmonics are also present on the system [9]. The figure 6 shows the typical voltage waveform measured in the socket. Here we observe that some of the signals are almost a perfect sinusoid, while others come close to a staircase.

While almost close 50Hz the frequency of the primary signal is continuously changing, reflecting current conditions on the grid. These small changes in frequency give the information about the operation of the grid. That is changes in frequency indicate mismatches between generation and load. The characteristics of these changes are indicative of the performance of the power grid.

(ii) Event detection

Information on operational characteristics of grid can be observed by frequency data. Frequencies too far from the nominal level can cause damage to equipment and are indicative of abnormal events [9]. Large rapid frequency shifts are also indicative of specific problems occurring on the grid, such as a power plant going offline for some reason.

For a number of years, utilities and transmission line operators have been able to use data from phase measurement units to access the impact of large disruption. Similar observation can be made using data from power outlets. Other interesting event is islanding, [9] the occurrence this event is detected by observing frequency response of the grid. The figure 8 shows the frequency deviation at the event of islanding.

Thus by continuous monitoring the power grid will establish a record of performance and flow changes and impacts to be observed, particularly the new technologies like renewable generation and other devices come online and start to have an impact on the operation.
of the power grid. The signal processing advanced algorithms gives better control and monitoring of the power grid.

II. CONCLUSION

This literature review presented the smart grid challenges and the possible solutions in signal processing perspective. To support information interchange, grid itself acts as communication medium in PLC technology. To deploy this technology the challenges and the solutions were discussed. The information consists of data as well as control information of the system therefore the communication should be secure and risk free from bad data injection. This problem is solved by advanced signal processing algorithm. Demand response based pricing improve the power consumption and it support the reliable operation of grid system. EVs charging may load the grid so that the techniques are discussed to manage the peak load with the help of PMUs. And finally monitoring the grid system gives information about the operational characteristics and power quality issues. Observing the grid waveform and analysing frequency response with signal processing techniques provide better results on theft, event detection,(sag, swell, interruptions etc) islanding and harmonics. In smart grid bidirectional flow of information and power meet the challenges beyond this discussion are state estimation, Integration of micro grid and frequency estimation.

REFERENCES