# A New ICT-based Modeling for the Power Grid

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Abstract: The purpose of this work is to propose a new theoretical and mathematical model that describes the energy flow over a microgrid, à small portion of a power grid. Indeed, there is similarity between a transmission channel made up of several transmitters/receivers and the microgrid involving various energy sources/consumers. This has been the premise which prompt us to conduct this study and develop a new model of the microgrid. The propounded model is not to contest or to interrogate electromechanical results about the flow of electricity. It rather brings another way of seeing the energy flow. Moreover, this framework bears in mind intermittent energy sources. The inclusion of renewable energy sources in the conventional power grid has to be taken into account in order to come up with a model that is faithful to the current state of the grid. On the basis of a MIMO (multiple-input and multiple-output) channel, the proposed architecture consists of a Single Virtual Power Source (SVPS) serving its energy at several energy consumption points. Its energy flow's shape is a Gaussian as it will be demonstrated throughout this paper.

## 1 INTRODUCTION

An expertise of the microgrid is one of the most current crucial matter. Understanding, modelling the architecture of such a system, from an electrical point of view, which connects electricity end-consumers is of absolute necessity. This turns out to be even more significant due to:

- the integration of information and communication technology "ICT" into the grid (it is undergoing many transformations which make it complex);
- The integration of less predictable energies sources such as solar, wind ... which can degrade the reliability and quality of service of the grid;
- Taking into account new electrical uses like the electric vehicles, a multitude of electrical and electronic devices that increase the demand for electricity ...

Therefore, it is capital to understand the functioning of the power grid for further improvements. The aim of this paper was to look into the power grid demeanour and establish a new mathematical model that brings to light the flow of energy throughout a microgrid, because the existence of such a model could lead to sustainable research.

To back our results up, a brief but consistent overview in the literature about power grid models in terms of electricity flow was done. The most common power grid model is presented by (Grainger and Stevenson,1994), (Andersson, 2008), and (Zimmerman and Murillo-Sanchez 2015). This model relies on elements suitable for power flow analysis such as lines and cables, transformers, shunt elements, loads, generators... It gives the expressions for the active and reactive power flows along the power grid.

One of the solutions proposed is called "load-flow study", which is a numerical analysis of the flow of electric power in an interconnected system. It is based on non-linear relationships between voltage and current at every bus system. Generally, for each grid of $n$ independent buses, we can write $n$ equations relating voltage to current as follows:

$$\begin{cases} Y_{11}V_1 + Y_{12}V_2 + \cdots + Y_{1n}V_n = I_1 \\ Y_{21}V_2 + Y_{22}V_2 + \cdots + Y_{2n}V_n = I_2 \\ \quad\quad\quad\quad \dots \\ Y_{n1}V_1 + Y_{n2}V_2 + \cdots + Y_{nn}V_n = I_n \end{cases} \tag{1}$$

where $I$ is the vector of $n$ currents injected into the bus, $V$ is the vector of the $n$ bus voltage, and $Y$ is called the admittance matrix buses. This approach follows Kirchhoff's circuits laws. Its aim is to get the magnitude and phase angle of the voltage at each bus. It requires knowledge of a variety of information at each bus.

The mathematical model that we propose in this



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paper has been developed under the assumption that our microgrid connects households at the same level of voltage. The problem was then to study an energy flow through an electric cable that covers a well-defined area.

We started with a lumped equivalent model of an electric cable, and, through its communication channel model, we tried to extricate a model that describes the electrical energy flow over a power grid.

The structure of this paper is as follows: In section II we talk about the microgrid and then briefly present the electromagnetic wave propagation on a wire. In section III, with the help of a probabilistic approach, we present a Single Input Single Output (SISO) Power Line Communication (PLC) modeling. On the hinge of these two descriptions, we propose a new model that describes the flow of energy throughout the microgrid in Section IV. Finally, in section VI we end our work with a brief conclusion, but that sums up well our contribution in this research area.

# 2 SYSTEM MODEL

## 2.1 Microgrid

According to (Association Smart Grid Suisse, 2016), a smart grid is an electrical grid linking electricity production, consumption and storage, and coordinating them autonomously. Within a smart grid, Information and Communication Technologies play an essential role: By providing a two-way and real-time communication between all components of the power grid, they make it possible to control every point on the grid to ensure its efficiency, reliability and durability in an intelligent and automated manner. The intention is a constant regulation of electrical energy, where there is a counterbalance between the energy produced and the energy consumed.

However, the implementation of such systems encounters many difficulties. Except for a few research projects, nowhere in the world exists a smart grid that has fully automated control of consumer devices and production facilities (Association Smart Grid Suisse, 2016). As a result, the deployment of small smart grids, commonly called microgrids, is seen as "a simpler alternative to implement and could therefore play a leading role in the deployment of smart grids" (Smart Grids-CRE, 2017).

A microgrid is a grouping of interconnected loads and decentralized energy sources in an area whose electric boundary is clearly defined, and which acts as a single controllable entity with respect to the main grid (Office of Electricity Delivery & Energy Reliability, 2015). It can operate either in stand-alone (island) mode, connected to the main network or switch between these two modes.

The microgrid studied in this paper delimits a residential neighbourhood whose households are represented by the index $i$, varying from 1 to $n$. As it has been mentioned, the whole network is at the same voltage level, i.e., The last electrical substation closer to the electricity-consuming elements is located to the interconnection point of the microgrid to the conventional power grid (a delivery substation generally of 20 kV / 400 V). Figure 1 shows the model of our microgrid.

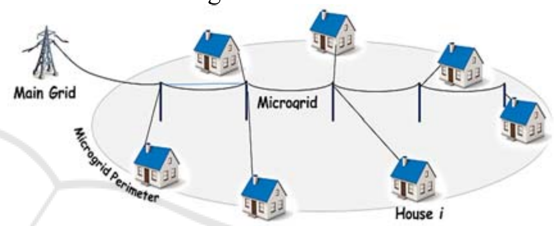


Figure 1: Microgrid representation.

Each house $i \in [1, n]$ has its specific electricity needs Ni and, depending on available energy sources (solar/wind/fuel cell), it can produce an amount Pi of electricity.

## 2.2 Electromagnetic Wave Propagation on an Electric Wire

Electromagnetic wave propagation results from the evolution and progression of a wave within a medium. Propagating in an electric wire, the transmitted signal undergoes various phenomena such as reflection, signal attenuation, multipath phenomenon… This means that there will be many received signals which are distorted, mitigated and delayed.

Let's consider a small portion of an electric wire. Because of the wire imperfect constitution, the wave propagation is characterized by a distortion in terms of distance and frequency. By applying the transmission line theory on a $d$ length line without derivation, such as that illustrated on Figure 2, the frequency response of the section is then written:

$$H(f) = \frac{U(x = d)}{U(x = 0)} = e^{-\gamma(f)d} \quad (2)$$

Where $U$ is the voltage on the line at the distance $x$

and γ represent the propagation constant of an electromagnetic wave.

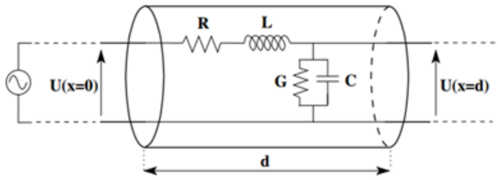


Figure 2: Equivalent lumped elements of a transmission line model.

The propagation constant for any conductor is calculated from the primary line coefficients by means of the equation bellow:

$$\gamma(f) = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (3)$$

Where $\omega$ is the angular frequency. The real part $\alpha$, and the imaginary part $\beta$ of the propagation constant represent respectively the attenuation constant and the phase constant. (Errede, 2015) gives a very detailed demonstration of this.

In a typical scenario, an infinite number of propagation paths is theoretically possible (several observable reflections on the wire). This is due to the electrical grid impedance which practically always mismatches. The frequency response of the section is then transformed as:

$$H(f) = \sum_{i=1}^{N_p} g_{i(f)} e^{-\gamma(f) d_i} e^{-j2\pi f \tau_i} \quad (4)$$

Where $g_i$ and $\tau_i$ are respectively the ponderation factor and arrival time of a multipath component $i$. $N_p$ is the dominant number of paths (Zimmermann and Dostert, 2002). The gain term $g_i$ reflect the product of the reflection and transmission factors experienced by the $i$ path as shown on Figure 3. The ratio between the distance $d_i$ and the wave propagation velocity $v_i$ is equal to the delay $\tau_i$. $v_i$ depends on the type of material that made up the line. Note that $\gamma$ depends on the resistance $R$, inductance $L$, the conductance $G$ and the capacitance $C$, which are characteristic properties of the transmission line.

Moreover, the reflection and transmission coefficients differ from one grid to another. Thus, the electric characterization of the grid needs prior knowledge (the intrinsic characteristics of power lines): This is called a bottom-up characterization.

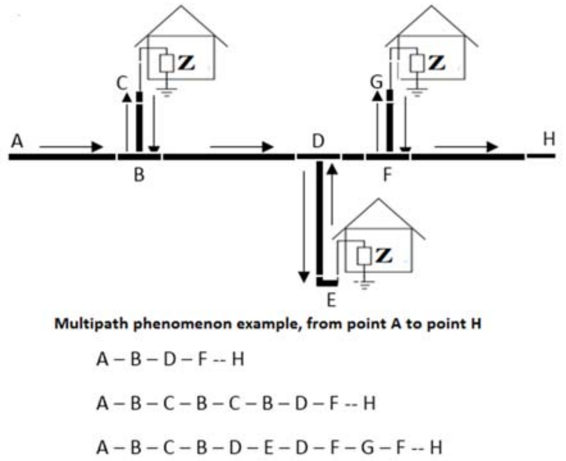


Figure 3: Signal propagation over a transmission power line.

# 3 POWER LINE COMMUNICATION

A PLC channel model was firstly formalized by Zimmerman (Zimmerman and Dostert, 2002). It is a system that transmit information on an electric wire operating at any voltage stage. Equation (4) of the preceding section actually introduces the PLC channel characterization using the determinist approach. It has been pointed out that knowing the characteristics of the electric wire is necessary. This means a lot of resources and much time, without guaranteeing an extrapolation of the model to another grid (other than the one studied).

A statistical model turns out to be of great necessity to take into account of a larger amount of cases. The passage of the frequency response into the time domain by the inverse Fourier transform gives us the impulse response of the PLC channel. It is expressed as:

$$h(t,\tau) = \sum_{i=1}^{N_p} g_i(t) e^{-j\theta_i(t)} \delta(t - \tau_i(t)) \quad (5)$$

Where each $i$ path is characterized by its propagation delay $\tau_i$, the attenuation factor $g_i$ and phase $\theta_i$. In fact, every transmitted signal undergoes interactions like electromagnetic reflections, diffractions, refractions, and each of these interactions induces a phase for each path.

Let's apply the PLC we have introduced above on the microgrid presented on Figure 1, where houses communicate one another (Single Input Single Output). If we assume that the signal remains the same for periods of time superior to the duration of the information symbols, as done in (Canete, 2003), the PLC channel can be considered time-invariant. Thereby the model proposed by Bello (1963) known as Wide-Sense Stationary Uncorrelated Scattering (WSSUS) can adopted to model our propagation channel. This model considers that the impulse response is wide-sense stationary and the different paths are uncorrelated.

Note that, within our microgrid, the distance between the transmission and reception would not vary over time, the Doppler Effect will not be considered in the following channel characterization. The complex impulse response of the PLC channel becomes then:

$$h(t) = \sum_{i=1}^{N_p} g_i e^{-j\theta_i} \delta(t - \tau_i) \qquad (6)$$

# 4 ELECTRICAL POWER FLOW MODEL

Let's come back to the real issue of this paper, namely the power flow modeling. Considering both energy sources and needs within the microgrid on Figure 1, the flow of electricity from one house to another could be schematized as displayed on this figure:

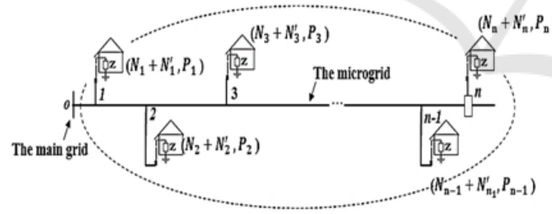


Figure 4: The microgrid's energy flow elements.

Where:

- $P_i$ expresses energy injected by house $i$ onto the microgrid
- $N'_i$represent house $i$ energy needs handled by energy produced on place (the same house $i$)
- $N_i$ represent residual energy needs of house $i$ which are to be handled by other energy sources
- The sum of $N'_i$ and $N_i$ speaks for the total energy needs of the house $i$

Based on this architecture described, energy flow at a given house $j$ is run by the two equations:

$$N_j = \left[G_{j1} \cdots G_{ji} \cdots G_{jn}\right] * \begin{bmatrix} P_1 \\ \vdots \\ P_i \\ \vdots \\ P_n \end{bmatrix} + L_{j0} * m \qquad (7)$$

$$P_i = P'_i - N'_i \qquad (8)$$

Where:

- $G_{ji}$ reflects line losses of injected energy $P_i$ , from any house $i$ toward house $j$
- $m$ stands for energy provided by the main grid
- $L_{j0}$ is $m$ line losses occurred from point 0 to house $j$
- $P'_i$ represents the energy produced by house $i$

It is obvious that when $i = j$ the house that injects energy corresponds to the house for which the needs are calculated. In this case, there is no line losses ($G_{jj} = 1$). This means that row vector $G$, named weighting factor by the following, is inversely proportional to the line losses it represents.

$$0 < G_{ji} \leq 1 \qquad (9)$$

Considering the whole system, it is clear that energy at the point of usage $i$ equals to the energy produced at same point $i$, plus the energy produced elsewhere, obviously after suffering losses during transport. This is to say that, in terms of energy flow, our system includes multiple energy inputs $P_i$, multiple energy outputs $N_i$ and multiple paths that energy borrows to get from one point to another. The energy mix is then expressed as follow:

$$\underbrace{\begin{bmatrix} N_1 \\ \vdots \\ N_n \end{bmatrix}}_{N} = \underbrace{\begin{bmatrix} G_{11} & \cdots & G_{1n} \\ \vdots & \ddots & \vdots \\ G_{n1} & \cdots & G_{nn} \end{bmatrix}}_{G} * \underbrace{\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix}}_{P} + \underbrace{\begin{bmatrix} L_{10} \\ \vdots \\ L_{n0} \end{bmatrix} * m}_{M} \qquad (10)$$

Which can be also written $N = G * P + M$, where column vectors $N$, $P$, $M$ represent respectively the houses energy needs, the houses injected energy and the main grid energy (basically energy outside the considerer microgrid).

$G$ is an $n$-by-$n$ matrix that represent the weighting factor of each path I of energy flow all along the microgrid. It is clear that $G_{ji} = G_{ij}^T$. $G$ is a symmetric matrix whose all main diagonal elements equal to 1(they stand for both the production and the consumption of energy at the same house: this means that there is no line losses).

Note that the second part of the equation is composed of a sum of the energy sources. This was done on purpose in order to propose to consider electricity as if it comes from a single source: A

Single Virtual Power Source (SVPS). Figure 5 illustrates this.

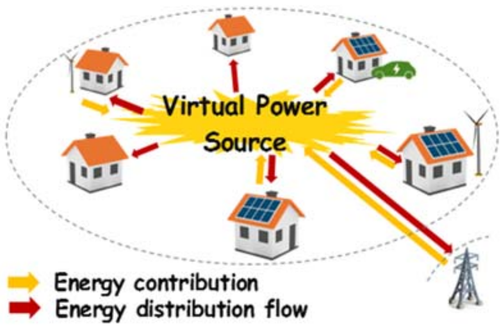


Figure 5: Single Virtual Power Source architecture.

The SVPS energy comes from different sources $P_i$ strewed throughout the microgrid. Virtually, this energy makes it to the SPPS with an asynchronous. It is due to the fact that energy is neither produced nor injected onto the microgrid at the same time. This randomness of the energy includes a delay $\tau_i$ during each $P_i$ accounting in the virtual source. The energy of our SVPS $E_{tot}$ is therefore given by:

$$E_{tot}(\mathrm{t}) = \sum_{i=0}^{n} P_i\,(\mathrm{t} - \tau_i) \qquad (11)$$

Where $P_o$ stands for energy provided by the main grid (sources other than microgrid's), and $(P_1, \cdots, P_n)$ represent energy injected by different houses of the microgrid.

Moreover, the electricity delivered by this virtual source passes through various paths $d_i$, while it goes to the different houses to meet their needs. As displayed below, these two things combined reveal a multi-path phenomenon in our architecture.

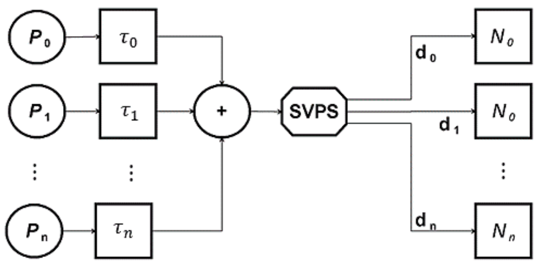


Figure 6: Multipath phenomenon of the SVPS architecture.

Relying on the architecture that we have described, we can observe a strong resemblance between the energy flow represented in Figure 5 and the transmission of an electromagnetic wave over a PLC channel described in its section III.

Table 1: Analogy between the PLC channel and the proposed model based on a single virtual power source.

| PLC | Proposed power grid model based on SVPS |
|---|---|
| Transmitter | Single Virtual Power Source |
| Receiver | House *i* |
| Multipath phenomenon from transmitter to receiver due to the high frequency | Multipath phenomenon due to the relation between the SVPS and house *i* |
| Scattered signal as a function of time | Line losses as a function of distance |

In the case of a PLC, the propagation delays from various paths vary randomly and as we said. So a large number of propagation paths is unavoidable. The resulting signal is a sum of a random module and phase components. Thus equation (6) is approached by a complex variable whose quadrature components $I$ and $Q$ are independent and trail a Gaussian distribution. The envelope of this signal follows a Rayleigh law defined by the following equation:

$$f(r) = \frac{r}{\sigma^2} e^{\frac{-r^2}{\sigma^2}} \qquad (12)$$



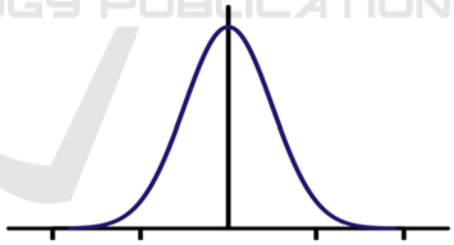

Figure 7: Shape of the impulse response of a typical Gaussian filter.

With $r = \sqrt{I^2 + Q^2}$. σ is the standard deviation of the real part $I$ or imaginary part $Q$. From a probabilistic point of view, the randomness of equation (6) means that its realization converges to a known form: The Gaussian shape representation in time domain is illustrated by this:

As it has been evoked previously, energy that will be delivered by our virtual source $E_{tot}$ is the sum of all the energy sources at the level of the microgrid plus energy from the main grid. Furthermore, through the study conducted in this paper, similarity has been pointed out between the

PLC and our system. The resemblance between the proposed model and the radio channel is not physical, but rather mathematical: For the PLC model, the transmitter is a time invariant source unlike the channel which might be variant if we take into account the impact of loads on the wave propagation.

Regarding our model, energy flows over a time invariant channel (households therefore charges are at known positions) but the SVPS is time variant due to asynchronous of the energy production mentioned above. Thenceforth the same applies to our microgrid. The electrical energy flow $E(d)$ within the microgrid can be expressed as:

$$E(d) = \sum_{i=1}^{n} g(d_i) E_{tot}(d - d_i) \quad (13)$$

The energy flow is a function of the distance $d$, where $g(d)$ reflects the temporal asynchronous of the energy injection onto the grid and energy line losses heading to different point of usage (house $i$). It is a summation of several random phenomena, both temporal and spatial.

This resemblance between equation (6) and (13) leads us to conclude that the energy flow is Gaussian-shaped. However, this first study represents the foundation of further work that is to follow. It will consist in the model validation, preferably by real data, or by simulations on appropriate platforms.

## 5 CONCLUSIONS

While there are still many questions about models of a power grid, and many possible ways to address this issue, our aim in this paper was to propose a new model of the electric flow: Disregarding the need of knowing different parameters of the grid at each bus (active power, reactive power, power factor), we demonstrated that a microgrid can be assimilated to a transmission channel which conveys energy from a Single Virtual Power Source to multiple energy consuming points.

In regards to the energy flow, equation (6) whose shape is characterized by a Gaussian was utterly approximated by equation (13). This is due to the fact that the whole energy flowing through the grid is actually a sum of a certain random amount of energy injected by different sources. This is also braced by the fact that energy undergoes various phenomena such as line losses and multiple scattering due to different paths.

The proposed mathematical model will be of precious assistance in the smart grids: For example, during the grid characterization, the development of energy allocation strategies…

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