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# Regression and kriging analysis for grid power factor estimation

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**Abstract**

The measurement of power factor (PF) in electrical utility grids is a mainstay of load balancing and is also a critical element of transmission and distribution efficiency. The measurement of PF dates back to the earliest periods of electrical power distribution to public grids. In the wide-area distribution grid, measurement of current waveforms is trivial and may be accomplished at any point in the grid using a current tap transformer. However, voltage measurement requires reference to ground and so is more problematic and measurements are normally constrained to points that have ready and easy access to a ground source. We present two mathematical analysis methods based on kriging and linear least square estimation (LLSE) (regression) to derive PF at nodes with unknown voltages that are within a perimeter of sample nodes with ground reference across a selected power grid. Our results indicate an error average of 1.884% that is within acceptable tolerances for PF measurements that are used in load balancing tasks.


*Keywords:* Kriging; LLSE; PF measurement; Transmission and distribution; Utility grid; Variogram

## 1. Introduction

Power factor is a measure of power utilization by a load and is a well-known and often used parameter in power distribution. The smaller the power factor, the higher the current utilized by the load and this is not efficient for the power supplier. The power supplier always tries to establish a reasonable PF (above 0.8 or 0.9) (Krein, 2004) in an electric grid to meet power certification requirements such as the IEC 61000-3-2 and 80 PLUS in the United States. Similar constraints are used worldwide. These requirements vary according to end users; e.g., industrial, commercial and residential customers. When we look to a standard housing complex in terms of power distribution, various kinds of loads are on and off for indefinite periods of time, so PF at residential sub-grids is always varied. Some form of monitoring is required to overcome the undesired losses.

Effective usage of electrical power, particularly that in the utility grid, is under constant surveillance and study. The efficiency of power in the grid is calculated in terms of PF, which is a phase relationship between the components of

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power, voltage and current. Measurement of PF allows the supplier to determine at which points in the grid remediation should be concentrated to improve low power efficiency.

The ENERGY STAR program for external power supplies requires manufacturers to mark their devices using the international efficiency marking protocol. Any external power supply meeting the performance requirements for level V and above would qualify as an ENERGY STAR (Version 2.0) (International, 2008) appliance. Power supplies with performance levels of I–IV would not qualify under the Version 2.0 ENERGY STAR specification, which has been in effect since November 1, 2008. With respect to these specifications, a power distributor cannot be 100% sure that consumer is using only level V qualified loads. Autonomous monitoring of the PF variation as we discuss here gives suppliers and distributors an estimate of accumulated losses that would help them to analyze and take corrective actions to improve efficiency. PF correction techniques will vary according to the polarity of the PF. These corrections can be costly and improper usage of corrective techniques will incur a greater magnitude of loss than if none were applied.

For measuring the PF, both current and voltage waveforms are required. Current can be measured easily at any desired point in the grid using current tap transformers; however, measuring voltage requires access to a ground connection, so the measurement of voltage at any desired point in a grid is more difficult to do than that of current. Monitoring PF across all the desired points in the grid with measuring devices is not efficient. One solution to this situation is to approximate the voltages using only their current measurements along with current and voltages known at select locations in the grid using constrained approximation regression analyses. This is the basis of the work presented here.

In these approximation methods we have used PFs as the training values rather than voltages. This has revealed the PF estimation directly at the unknown points, which is our final desired approximation across the grid under evaluation. Doing this makes the work simpler than estimating the voltages and then deriving PFs from them. In an automated, distributed system it would also make the implementation simpler and more robust.

## 2. Related work and analysis methods

### 2.1. Kriging analysis

Kriging is defined as a random value interpolation based on nearby observations that are weighted according to spatial covariance values (Kriging-GSM Implementation; Bohling, 2005). Interpolation of parameters is treated as a regionalized variable and is intermediate between a truly random variable and a completely deterministic value. Kriging estimation weights are derived from a covariance matrix and the method employs the concept of the *semi-variogram*, a function that characterizes the residual components on which the residual estimation of a desired location is dependent. From a covariance model, the estimated variance is minimized. Kriging methods generally are of three kinds: simple, universal and ordinary.

In simple kriging, a particular region is considered from all the available points and is analyzed. In universal kriging, it is applied region-wise and thus the entire available set of points is analyzed. Universal kriging is performed when very large amounts of data or points of measurement are available. Ordinary kriging follows the original development of the method as described in a thesis by Krige (1951). Kriging semi-variograms are of different types depending on the application and these types include spherical, exponential, and Gaussian amongst others.

#### 2.1.1. Characteristics of the semi-variogram

The *sill* is the semi-variance value at which the variogram levels off, as shown in Fig. 1. The sill is generally 1.0, but may have lesser values. *Range* is the lag distance at which the variogram reaches the sill. If the variogram does not start from zero, the difference is termed the *nugget*. Overall sill is the difference between fundamental sill and the nugget.

Fig. 2 illustrates the morphology of spherical, exponential, and Gaussian variograms. From this it should be clear that the spherical variogram reaches the sill earlier than the exponential and Gaussian. So, the spherical variogram is what was considered to employ with the kriging method used here since the equation that reaches the sill earlier yields a better approximation, which our results confirmed.

The variogram equations are:

$$\text{Exponential} \quad C(h) = c\left(1 - \exp\left(\frac{-3h}{a}\right)\right) \tag{1}$$