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Application of statistical process control chart for monitoring electric power losses through transmission and distribution system: A case study

Mohammad Shamsuzzaman[*], Eman Jasim and Imad Alsyouf
Sustainable Engineering Asset Management (SEAM) Research Group
Department of Industrial Engineering and Engineering Management, College of Engineering
University of Sharjah, UAE
*mshamsuzzaman@sharjah.ac.ae

Abstract

Monitoring and controlling of electric power losses have high importance in any power distribution utility, since reducing system loss is one of its main objectives. System loss is a combination of technical and non-technical loss. Current practices suggest using different technical devices such as appropriate-size transformer and low voltage capacitor in controlling the technical losses, however, it is impossible to control the non-technical losses using such devices because it happens as a result of actions external to the power system (e.g. meter inaccuracies and/or power theft). Statistical Process Control (SPC) tools are being used broadly in areas outside the manufacturing industries in recent years since they showed their effectiveness in continuous monitoring and improvement. In this study, *X*&*MR* control chart is used for monitoring power losses through transmission and distribution system. The concept is discussed and illustrated through a case study. The results of the study show that the SPC chart is able to detect the unusual power losses successfully.

Keywords
Statistical process control, control chart, electric power losses

1. Introduction

The electrical power system consists of three stages such as generation, transmission and distribution. The electric power is first generated in bulks at the generation stations; usually the generation stations are located far from where electricity is demanded, thus, the generated power goes through transmission and distribution network to reach the final consumers (Bakshi and Bakshi, 2009). Transmission (T) is moving a large amount of high voltage power over long distances, where distribution (D) is taking the high voltage power form transmission grid, step it down and deliver it to load locations such as residential or commercial areas. The movement of electric power through T&D network results in some losses, which can be estimated by the difference between the generated power and the consumed power. The T&D losses are very high in many countries. For example, a recent study shows that the T&D losses are about 20% of generation in India, which is more than twice the world average and nearly three times as large as T&D losses in the United States (EIA, 2015). As a result, the financial losses due to power losses are critical to many electric power generation companies. Lost earnings can result in lack of profits, shortage of funds for investment in power system capacity and improvement (Smith, 2004). Monitoring and controlling of power losses have high importance in ensuring system stability in addition to reducing the amount of required electricity production to meet demand (Al-Hinai, 2013).

The main objective of a power utility is to maximize the utilization of electric power that will be delivered to the end consumer in a very secure and efficient way. Thus, the power system efficiency has a very high importance, where a high rate of system loss is one of its major contributors. Power system loss consists of two main types: Technical Loss (TL) and Non-Technical Loss (NTL). Technical loss is mainly due to the physical properties of the power system components (e.g. internal resistance, transmission lines, power transformers and measurement instruments). To decrease technical loss, it is suggested to select an appropriate-size transformer and to install low voltage capacitor (Sandhu and Maninder, 2013). On the other hand, non-technical loss is mainly happened as a result of actions external to the power system, and at the same time, internal to overall management of the utility (Jiménez *et al.*, 2014). The non-technical loss is due to metering inaccuracies, meter tampering, bypassing and/or theft. Technical loss is easier to compute and control due to the improvements in information technology and data acquisition systems (Navani *et al.*, 2012). However, non-technical loss is more difficult to measure because usually there is no recorded information on this type of loss and there is no control on the customer behavior. The prepaid energy meters and an integrated billing systems can be used in reducing the NTL, moreover, a statistical monitoring of energy consumption and evaluation of meter reading could be done (Navani *et al.*, 2012).

The SPC tools were mainly applied for process control and improvement in manufacturing industries for over fifty years, where, control charting has been the most common process control technique. Control chart is generally recommended for monitoring a process over time to identify any changes or trends. A control chart is a graphical display of a quality characteristic against time (or sample numbers) with control limits; it shows the statistically significant deviation from the norm which could be due to assignable causes where investigation is required. The design and application of control charts in nonmanufacturing industries is a challenging task as the nature of the quality characteristics are quite different from those of the manufacturing industries. Many researchers emphasized on the publications of case studies showing the benefits of Statistical Quality Control (SQC) (Woodall and Montgomery, 1999). In the recent years, the number of publication on the application of control charts outside the manufacturing area has been increased, for example, engineering, industrial and environmental applications, healthcare applications, and general service sector applications (Scordaki and Psarakis, 2005). Wood (1994) used a standard mean control chart to monitor the time taken to respond to external telephone calls in a leisure centre. The target was 98% of calls answered within three rings. The charts showed that 58% of calls were answered within the targeted values. The application of the control chart gave a clear feedback on the success and the requirement of the improvement. Wood (1994) presented another fraction non-conforming control chart for monitoring the proportion of complaints to an environmental health department. Jones and Dent (1994) carried out a pilot study within the staff restaurant using SPC to analyze the variety of food, temperature of food and the hygiene in the staff restaurant. These three variables were monitored using $\overline{X}$ & R charts. It was shown that all three variables had acceptable performance levels, and none of them was outside the accepted tolerance level. Latzko (2000) used c-chart to monitor and control the customer complaints, where the average number of complaints for one month was plotted. Scordaki and Psarakis (2005) presented an application of Shewhart type control charts in sales data. To check the stability and the attribution of each salesman, independent Shewhart type control charts were applied for individual observations. Mobin *et al*. (2015) proposed a multi-objective model for design of a control chart. In addition, Tavana *et al*. (2016) proposed an integrated solution methodology to solve the multi-objective design of $\bar{X}$ control chart. The available literature shows that the applications of SPC tools in nonmanufacturing organizations are increasing rapidly due to the current emphasis on Total Quality Management (TQM). One of the areas where SPC tools could be applied in is the power engineering area, where continuous monitoring and controlling are very important in order to ensure high levels of quality and efficiency. The importance of power losses reduction rises due to the increasing cost of power generation and shortage in fuel. Therefore, the system losses should be monitored and controlled so that it is not exceeded the target established by the utility. Motivated by Navani *et al*. (2012), this study attempts to design a SPC chart for monitoring power losses through transmission and distribution system.

2. Methodology

2.1 Selection of the control chart

Control charts can be classified into two main types such as variable control charts and attribute control charts. The variable control charts are used for monitoring variable (quantitative) type quality characteristics. The widely used variable type control charts are the Shewhart 3-sigma control charts such as $\overline{X}$ & R, $\overline{X}$ & S, and X&MR charts. The $\overline{X}$ & R or $\overline{X}$ & S control chart is used for monitoring process mean and variability (sample size, $n > 1$). Whereas, X&MR chart is used for monitoring individual measurement ($n = 1$); the first chart (X chart) plots measurements around a mean value, and the second chart (Moving Range (MR) chart) records the size of the change in the control chart from one observation to the next; it is a measure of variation and is used to calculate the control limits of the

X&*MR* chart. On the other hand, attribute control charts are used for monitoring attribute (qualitative) type quality characteristics. The traditionally used Shewhart 3-sigma attribute control charts are *p, np, c* and *u* charts. The selection of a control chart mainly depends on the type of the quality characteristics. In the proposed study, the quality characteristic is the power loss, which is measureable and thus a variable type control chart is used. It is decided to use *X*&*MR* chart as the objective is to identify the unusual power loss over time and the loss at each point of time is important. On the other hand, it may not be realistic to form a large sample (n > 1) as the power consumption will be measured based on monthly energy meter reading. For example, a sample of size five (n = 5) will need five months data which will make the sampling interval (h = 5 months) unusually very high and the use of the control chart may not be beneficial.

2.2 Design of the *X*&*MR* control chart

In quality control, the designs of control charts are completed in two steps known as Phase I and Phase II operations. In Phase I operation, m (at least 20 to 25) preliminary samples are taken. The purpose of taking the preliminary samples in Phase I is not to monitor the process, but to collect sufficient data so that at the end of Phase I, the in-control process mean and standard deviation (SD) can be estimated, and the control charts can be built. In Phase II operation, the control charts built at the end of Phase I is used to monitor the forthcoming data.

Assumptions

In designing the X&MR chart for monitoring power losses, it is assumed that the data on power losses are normally and independently distributed. Study shows that control charts are robust to the assumption of normality (Woodall, 2000). However, it is recommended to verify the assumptions of normality as it can help in identifying highly skewed data (Mohammed *et al*., 2008).

Deciding sample size and sampling interval

As decided, *X*&*MR* chart is used for monitoring each individual observation of power losses every month. In other words, the sample size is set at (n = 1) and the sampling interval (h) is decided to be (h = 1 month).

Calculation of control limits

A two sided X&MR control chart is designed for monitoring the power losses over time. The lower control limit (*LCL*), central line (*CL*) and upper control limit (*UCL*) of 3-σ X&MR chart can be calculated as follows.

Control limits of the *X* chart:

$$\begin{aligned} UCL &= \bar{X} + 3\frac{\overline{MR}}{d_2} \\ CL &= \bar{X} \\ LCL &= \bar{X} - 3\frac{\overline{MR}}{d_2} \end{aligned} \quad (1)$$

Where, $\bar{X}$ is the average of the observation X_i (i = 1, 2, ..., m) and $\overline{MR}$ is the average moving range of the moving ranges MR_i (i = 1, 2, ..., m). The moving range MR_i of a sample i is calculated by $MR_i = |X_i - X_{i-1}|$. The standard deviation (SD), σ can be calculated by $\sigma = \overline{MR}/d_2$.

Control limits of the *MR* chart:

$$\begin{aligned} UCL &= D_4 \cdot \overline{MR} \\ CL &= \overline{MR} \\ LCL &= D_3 \cdot \overline{MR} \end{aligned} \quad (2)$$

The constants d_2, D_3 and D_4 are obtained with respect to sample size.

The X&MR chart produces an out-of-control signal if any sample point plots beyond LCL and/or UCL of the X and/or *MR* chart. If a sample point falls above UCL, it is a signal that the power loss has been increased; conversely, when a sample point falls below LCL, it means that the loss has been decreased. However, if the sample points are plotted within the control limits but in a nonrandom or systematic fashion, it still indicates an out-of-control situation—this situation can be identified by using Western Electric rules (Montgomery, 2013). Thus, it is concluded that the process is out-of-control if one or more of the following points satisfied:

1. One or more sample points fall beyond the upper and/or lower control limits.

2. Two out of three consecutive sample points fall beyond the two-sigma limits.
3. Four out of five consecutive sample points fall beyond the one-sigma limits.
4. A run of eight consecutive sample points fall on one side of the center line.

3. Case Study

3.1 Data collection and analysis

The required data and information were collected from historical records of a power utility company. The name of the company is not mentioned here due to confidentiality. Because of the unavailability of data and information, this study does not distinguish between technical and non-technical losses, and the monthly total power loss in transmission and distribution (T&D) system are calculated based on the data on monthly total power generation and monthly total power consumption over six years (2009-2015). After excluding some loss data due to unrealistic values, the total number of samples were 57 (m = 57, n = 1).

3.2 Verification of the chart assumption

The data on the power losses were used to draw a normal probability plot as shown in Figure 1. It is seen that almost all the points are very close to the straight line and lie within 95% confidence interval, which is an indication that the data on the power losses are normally distributed (P-value = 0.103).

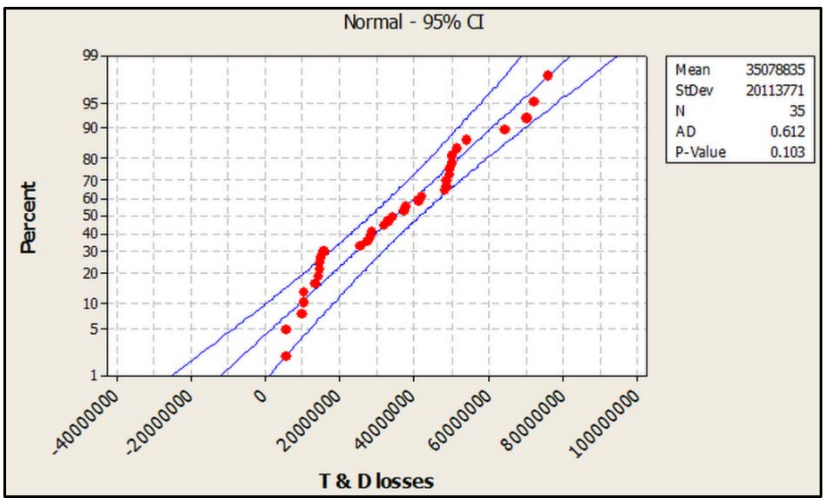

Figure 1. Normal probability plot of the data on the power losses

3.3 Monitoring of power losses using X&MR control chart

In Phase I operation, the first 60% of data on the power losses (i.e. m = 35) are used to design the X&MR chart (Figure 2). The purpose is to make sure that the losses is in statistical control and to finalize the control limits of the X&MR chart that can be used in monitoring the rest of the data on the power losses in Phase II. Figure 2 shows that all the 35 sample points are plotted within the control limits (for X chart: UCL = 90787162 kWh, CL = 35078835 kWh, LCL= -20629492 kWh, and for MR chart: UCL = 68437680 kWh, CL = 20946331 kWh, LCL = 0) of the X&MR chart, which means that the power losses are in statistical control. Moreover, none of the Western Electric rules is found to be satisfied conforming that the X&MR chart is in-control in Phase I. It is found from Figure 2 that on average the in-control power losses is 35078835 kWh, which is roughly about 20% of the net power generation of the company. This amount of power losses is quite high compared to power loss percentages in the developed countries that must not exceed 10% (Suryani *et al*., 2013). This finding highlights the importance of application of other SPC tools in addition to the control chart in order to identify and eliminate the root causes of the power losses.

The X&MR chart obtained at the end of Phase I is now used for monitoring the rest of the power losses data in Phase II (see second part of Figure 3). It is seen that all the sample points fall within the UCL and LCL of the control charts except three consecutive points (May, June and July 2014) that fall above the UCL of the X chart. The sample points which are above the UCL of the X chart indicate an out-of-control condition and needs further investigation to identify the assignable causes.

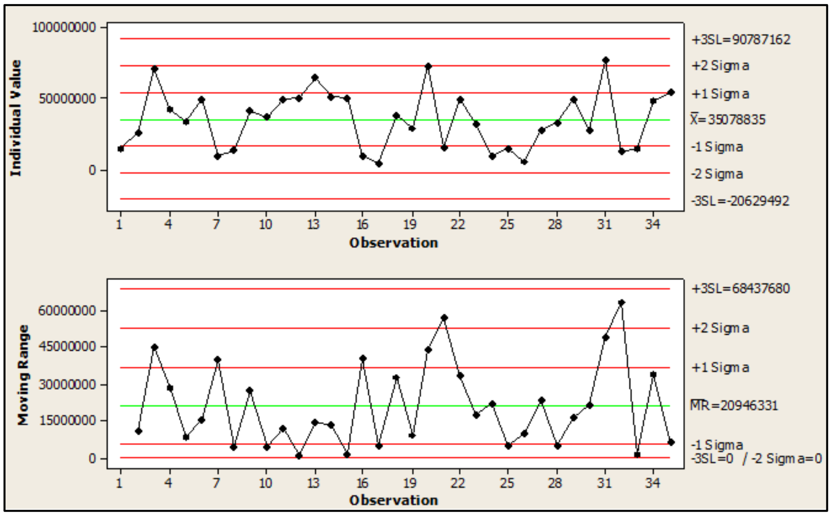

Figure 2. Phase I design of the $X\&MR$ chart

The investigation for the assignable causes showed that the unusual increase in the losses was due to two meter tampering cases as recorded in the violation report of the company. It clearly demonstrates that the unusual power losses can be identified by the control chart. Currently, the company does not use any system for monitoring the power losses (especially the non-technical losses). The non-technical assignable causes such as theft of electricity, bypassing, meter tampering, or an attempt to change the meter reading are difficult to identify. Usually, the company forms a team of some technical personnel to do a check on randomly selected users to detect such kind of violations. However, the implementation of the control chart can help the company to identify such violation immediately so that the corrective action can be taken in time to control the losses. Another advantage of implementing the control chart is that it allows the engineers to ignore random variations and focus on the real changes.

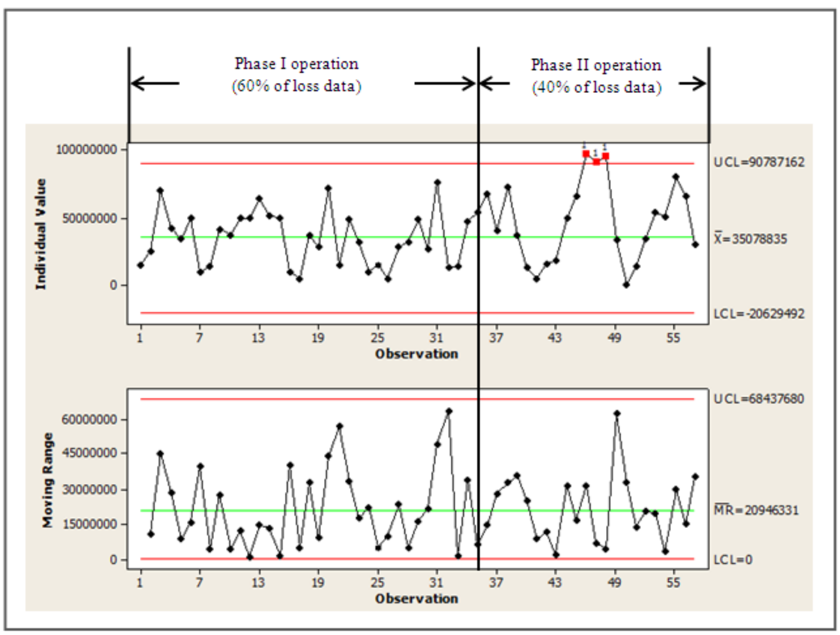

Figure 3. Monitoring of the power losses by the $X\&MR$ chart in Phase II operation

3. Conclusion

This article designs *X*&*MR* chart based on monthly electric power generation and consumption data for monitoring power losses through transmission and distribution system. It is verified that the designed *X*&*MR* chart are able to detect the out-of-control cases successfully. The designed control chart can be used as an assistive tool in identifying unusual power losses so that immediate action can be taken to maintain the power network stability, thus the defects to network equipments may be reduced and the network interruption may be avoided. Because of the unavailability of the data this study does not distinguish between technical losses and non-technical losses, however, to get more accurate result it is recommended to handle the technical and non-technical losses separately.

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Biography

Mohammad Shamsuzzaman is an Associate Professor in the Department of Industrial Engineering and Engineering Management at University of Sharjah, UAE. He obtained Bachelor in Mechanical Engineering from Chittagong University of Engineering and Technology, Bangladesh, Masters in Industrial Engineering from Asian Institute of Technology, Thailand, and PhD in Systems and Engineering Management from Nanyang Technological University, Singapore. His current research focuses on quality control, reliability, simulation and multi-criteria decision-making. He is a member of the American Society for Quality.

Eman Jasim is a professional engineer received her Bachelor degree in Electrical and Electronics Engineering from University of Sharjah, UAE. She has recently obtained Masters in Engineering Management from the same University. Her research interests include quality control and improvement, and optimization.

Imad Alsyouf is an Associate Professor of Industrial Engineering, currently employed by University of Sharjah, UAE, and previously worked at Linnaeus University in Sweden. His research interests include productivity improvement, performance measurement, life cycle cost analysis, reliability and maintenance engineering, and optimization of decisions at various phases of system life cycle. He has developed and taught more than 25 courses covering a wide range of Industrial Engineering and Management fields.