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Macroeconomic Assessment of Voltage Sags

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Abstract: The electric power sector has changed dramatically since the 1980s. Electricity customers are now demanding uninterrupted and high quality service from both utilities and authorities. By becoming more and more dependent on the voltage sensitive electronic equipment, the industry sector is the one which is affected the most by voltage disturbances. Voltage sags are one of the most crucial problems for these customers. The utilities, on the other hand, conduct cost-benefit analyses before going through new investment projects. At this point, understanding the costs of voltage sags become imperative for planning purposes. The characteristics of electric power consumption and hence the susceptibility against voltage sags differ considerably among different industry subsectors. Therefore, a model that will address the estimation of worth of electric power reliability for a large number of customer groups is necessary. This paper introduces a macroeconomic model to calculate Customer Voltage Sag Costs (CVSCs) for the industry sector customers. The proposed model makes use of analytical data such as value added, annual energy consumption, working hours, and average outage durations and provides a straightforward, credible, and easy to follow methodology for the estimation of CVSCs.

Keywords: voltage sag; cost; customer; interruption; reliability

1. Introduction

Power quality (PQ) has become a major issue for all participants of the electric power markets. On the customer side, the consumers demand continuous and high quality electric supply, while on the supply side, the authorities introduce more regulations so that the network operators will be able to provide the adequate service quality. At this point, power quality events and their corresponding technical and economic impacts that are experienced by the customers become a challenge for the electric power society. For the power system planners, it is imperative to understand the costs of power quality events in order to carry out cost-benefit analyses and to perform return of investment calculations of proposed investment plans for power system infrastructure. The major power quality events can be summarized as:

- Interruptions
- Voltage sags
- Voltage swells
- Harmonics
- Transients
- Flicker

Among all, the electric power interruptions and voltage sags are the most severe ones and therefore they pose the greatest danger to the suppliers and customers. IEEE standard 1159–2009 defines the interruptions and sags in terms of voltage magnitudes and event durations [1] as follows on Table 1:

Table 1. The Summary of Power Quality Events. PQ, power quality.

PQ Event	RMS Voltage	Duration
Interruptions	<0.1 p.u.	0.5 cycles–>1 min
Momentary interruptions	<0.1 p.u.	0.5 cycles–3 s
Temporary interruptions	<0.1 p.u.	3 s–1 min
Sustained interruptions	zero	>1 min
Voltage sags	0.1 p.u.–0.9 p.u.	0.5 cycles–1 min
Instantaneous voltage sags	0.1 p.u.–0.9 p.u.	0.5–30 cycles
Momentary voltage sags	0.1 p.u.–0.9 p.u.	30 cycles–3 s
Temporary voltage sags	0.1 p.u.–0.9 p.u.	3 s–1 min

Momentary and temporary interruptions are referred to as short interruptions, whereas sustained interruptions are referred to as long interruptions.

A review paper by Küfeoğlu and Lehtonen [2] compiled numerous significant studies regarding the costs of electric power interruptions. Nonetheless, due to its highly unpredictable nature, estimation of the economic losses due to voltage sags is more challenging. The characteristic of a sag can be defined by its magnitude, duration, the point-on-wave, the phase-angle jump, and unbalance. However, the most severe consequences of voltage sags depend on the magnitude and the duration of the sag as much as they depend on the sensitivity of the electrical equipment. The power quality performance of a consumer can be determined either by monitoring or by stochastic estimation. Several previous studies [3–5] provide in-depth studies for stochastic and probabilistic voltage sag impacts estimations. A study by Chan and Milanovic [6] introduced a failure risk assessment via fuzzy logic for the financial losses due to voltage sags. Another failure risk assessment study for modeling the voltage susceptibility for the industrial processes is provided by Chan et al. [7]. A study by Lin et al. [8] adopted the Tobit model to estimate economic losses due to voltage sags. On the other hand, monitoring stands as the best way of recording the characteristics of events and then calculating the corresponding Customer Voltage Sag Costs (CVSCs). However, as it is pointed out in [9], the level and the quality of measurement of poor quality events are not sufficient and reliable enough to estimate the economic losses due to these events.

Generic assessments of industrial process voltage sag performances are provided by [10–13] whilst [14–16] focused on hot-mill process, textile processes, and the automotive industry, respectively. Moreover, there have been previous case studies for the evaluation of voltage sag costs based on customers from Finland [13], Italy [17], Portugal [18], and Thailand [19]. Detailed information about the characteristics of voltage sags and technical impacts of these events can be found in [20,21]. Additional information about voltage sag indices is provided by the IEEE standard 1564 [22].

Voltage sags may result in discomfort for the residential customers. However, economic costs can increase considerably for commercial customers and can get bigger by many folds for industrial customers. In particular, the industry sectors that rely on continuous manufacturing and those which largely employ voltage sensitive devices, such as programmable logic controllers, control relays, adjustable speed drives, motor starter contactors, etc., are the ones which suffer the most due to voltage sags. Testing every single electric equipment's voltage susceptibility performance in case of voltage variations is practically impossible. Hence, in order to evaluate CVSCs in an efficient manner, instead of focusing on component-wise performance, a macroeconomic approach is needed.

The monitoring and measuring of voltage deviations in industrial facilities is a tedious task. The challenge increases by many folds when professionals attempt to estimate the economic costs of voltage sags. To overcome these drawbacks, this paper aims to estimate CVSCs with the aid of well-known knowledge and experience in electric power interruptions and their costs. This paper introduces a macroeconomic model that assesses CVSCs by linking the economic losses of voltage sags to those of short electric power interruptions. Section 2 presents the details of the macroeconomic model and explains how to relate customer interruption costs (CICs) with CVSCs. Subsection 2.1 is a recall section which is based on a previous study of the authors [23]. Section 3 includes a discussion and criticisms on existing approaches which estimate the costs of voltage sags and short interruptions. The causes and the elimination techniques of voltage sags or the analysis of the technical impacts of these events are not within the scope of this paper.

2. The Macroeconomic Approach

The consequences of short interruptions and voltage sags are not exactly the same, however, they are similar to some extent. Interruption of continuous manufacturing is the main common impact of these events for the industry sector customers. In order to provide a macroeconomic methodology for CVSCs in a way that will address large consumer segments rather than focusing upon particular customers and that can be utilized easily by system planners and utility operators, there are two main steps that need to be covered.

The first challenge is to come up with an analytical or macroeconomic method to calculate the customer interruption costs (CICs) for industry sector customers. After achieving this, the second phase will be to provide a relationship between the impacts of short interruptions and voltage sags so that CVSCs will be evaluated with the aid of CICs. This idea can be seen illustrated by Figure 1. To achieve the estimation of CVSCs by using publicly available and objective data, a step by step approach will be followed.

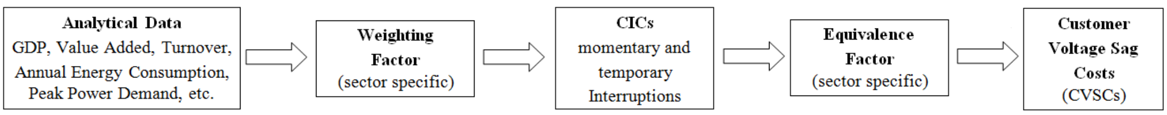

Figure 1. The block diagram of the macroeconomic approach for Customer Voltage Sag Cost (CVSC) calculations. GDP, gross domestic product; CICs, customer interruption costs.

In considering the first step, the aim of the following section will be to reach reliable and objective CIC estimations for momentary and temporary interruptions for various industry sector customers. In this step the main concern is to carry out the analysis process in a way that the need for extensive customer surveys will be kept to a minimum. This is crucial in order to decrease the level of subjectivity related to the surveying technique. The second step will be covered in Subsection 2.2, which discussed the concept of equivalence factors. The economic damages of short interruptions are equivalent to those of voltage sags up to some degree; the correlation between these two phenomena is discussed at this section. In Subsection 2.3, a novel voltage sag index, System Average RMS Variation Duration Index (SARDI), is introduced and the macroeconomic model is constructed with the aid of CIC, Equivalence Factor, and SARDI.

2.1. Weighting Factors and CIC

A novel Relative Worth (RW) approach introducing the evaluation of power outage costs for industry sector customers utilizes value added data of the customers and corresponding weighting factors so that the CICs can be calculated in a fast and straightforward manner [23]. The customer survey which the abovementioned study is based on classifies the cost types as follows:

Total losses = production losses + restart losses + losses of spoiled materials + damages + third party costs + other costs

From the interruption scenarios that last 1 h, 4 h, and 8 h the following coefficients were calculated for unexpected and planned outages respectively:

$$Ku = \frac{100}{percentage\ of\ production\ losses} \tag{1}$$

$$Kp = \frac{perc.\ of\ production\ losses + perc.\ of\ restart\ losses}{percentage\ of\ production\ losses} \tag{2}$$

The assumption behind defining the coefficients was that in case of an unexpected outage all types of losses are experienced by the customers, while for reported outages mainly production and restart losses are suffered since the consumer simply has the time to take precautions to minimize other cost types. Another strength of the RW method is that it divides the customers into subsectors and provides unique coefficients for each one. It should be kept in mind that the manufacturing processes of various subsectors differ considerably, and hence yield distinct CICs.

After defining unique weighting factors for each subsector, the Customer Damage Functions (CDFs) for unexpected outages (*CICu*) and for planned outages (*CICp*) were proposed:

$$CICu = Ku \times CICva \tag{3}$$

$$CICp = Kp \times CICva \tag{4}$$

where, *CICva* is defined as the Customer Damage Function (CDF) which adopts the value added of the customer in a year and normalizes it by the annual energy consumption. The CDF is calculated as follows by assuming that the annual working hours for industrial customers is 3000 h:

$$CICva\ for\ t\ hour\ per\ kWh = \frac{value\ added\ for\ one\ year}{annual\ energy\ consumption \times 3000\ h} \times t \tag{5}$$

This study has been conducted based on long interruption data. However, the characteristics of short interruptions, in particular momentary interruptions, differ substantially. Within the same customer survey the dominant cost types for 1 s of interruption per subsector can be observed summarized in Table 2. where 1 indicates that the cost type is significant and 0 means it is negligible:

Table 2. The Dominant Cost Types per Each Industry Sector for 1 Second of Interruption.

Sectors	Production	Restart	Spoiled	Damages	Third Party	Other
food	1	1	1	0	0	0
chemical	1	1	1	1	0	0
glass	1	1	1	1	0	0
paper	1	1	1	1	0	0
metal	1	1	1	1	0	0
timber	1	1	0	0	0	0
construction	1	0	0	0	0	0
electrical	1	1	0	0	0	0

It can be seen that the characteristics of consequences of short interruptions differ per each subsector. This was an expected finding, having considered that each customer segment has its own unique power consumption and hence will yield distinct economic losses due to outages. This argument can be supported by the findings of [24]. The study shows that the costs of momentary interruptions for textile sector customers is in the range of 2.0–4.0 $/kW, for electronics 8.0–12.0 $/kW, and for semiconductor manufacturing 20.0–60.0 $/kW. This is crucial in terms of opposing the idea of suggesting the same methodology to estimate the CICs or CVSCs for all industry sector customers. At this point it is imperative to provide more customer specific approaches to come up with more reliable estimations. Therefore, as it can be seen from Table 2, it is more credible to suggest the utilization of Ku coefficients for the food, chemical, glass, paper, and metal customer categories while Kp is more appropriate for timber, construction, and electrical subsectors. It should be noted that calculation of Ku covers all cost types where third party and other costs are negligibly small compared to the total losses. On the other hand, Kp stands only for production and restart losses. Therefore, for short interruptions it will be more reasonable to adopt Kp values for weighting factors instead of Ku values. These values have been calculated based on a customer survey conducted in Finland among industrial customers [23] and they are summarized in Tables 3 and 4.

Table 3. Typical Values of Ku Weighting Factors for Different Industry Sectors.

Sectors	1 h	4 h	8 h	Average
Food	1.96	2.01	2	1.99
Chemical	3.48	2.17	1.88	2.51
Glass	2.37	1.91	1.79	2.03
Paper	1.86	1.72	1.58	1.72
Metal	1.87	1.61	1.56	1.68

Table 4. Typical Values of Kp Weighting Factors for Different Industry Sectors.

Sectors	1 h	4 h	8 h	Average
Timber	1.3	1.18	1.08	1.19
Construction	1.16	1.15	1.15	1.16
Electrical	1.21	1.08	1.05	1.11

It should be noted that the calculation of Ku and Kp coefficients start from 1 h of interruption. Unfortunately, the customer survey does not include satisfactory data for the shorter outage scenarios. Therefore, in order to reach weighting factors which will correspond to interruptions from 0.5 cycles to 1 min, a regression analysis is carried out. Even though the CIC increases almost linearly for the first 8 h of interruption [25], for the sake of doing more sensitive estimation to calculate the short interruption weighting factors, a second order regression analysis has been conducted for further consideration. The results are summarized on Table 5.

Table 5. Weighting Factors (K) for 1 Second Interruption.

Sectors	Weighting Factor (K)
Food	1.93
Chemical	4.12
Glass	2.59
Paper	1.97
Metal	1.99
Timber	1.35
Construction	1.17
Electrical	1.27

2.2. *Equivalence Factors*

Previous studies have been undertaken to relate the evaluation of economic costs of these phenomena by proposing weighting factors [8,19,26,27]. According to the logic presented by McGranaghan and Roettger [26], the cost of the momentary interruptions are accepted as the base with a base factor of 1.0. After this, a weighting matrix is formed by assuming that a voltage sag with an RMS voltage below 0.5 p.u. will cause 80% of the economic damage of a momentary interruption, hence the weighting factor is to be 0.8. By following the same logic, it is assumed that a sag voltage between 50% and 70% will have a weighting factor of 0.4 and similarly a sag voltage between 70% and 90% will have a weighting factor of 0.1. Since these factors are meant to assess the equivalent damage of voltage sags to the interruptions, from this point on these factors will be referred to as equivalence factors.

While the percentages suggested in [26] use example values for a particular study, there were no grounds given for their widespread and generic use. On the other hand, Heine et al. [13] suggested that a voltage sag with a 0.5 p.u. RMS voltage will cause tripping in most of the load types. Thus, it should create the same impact with an interruption which will yield an equivalence factor of 1.0. However, McGranaghan and Roettger [26] claim that a sag with the same voltage level will have a 0.8 equivalence factor. In addition, it is clear that the sag duration has a certain impact on the degree of economic damage. reference study by Barr et al. [28] highlights this and calculates sag severities that change with changing sag voltage and sag duration. A 1.0 sag severity corresponds to a customer disturbance of complete interruption, while, for example, 0.5 severity is considered equal to an interruption where the total damage is 50% of a typical interruption. A voltage sag with a 0.30 p.u. voltage and a 0.17 s duration has a 0.55 sag severity, whilst a sag with 0.30 p.u. voltage and a 0.25 s has a severity of 0.65 [28]. Obviously the proposed methodologies for calculating the equivalent damage of sags and interruptions differ substantially. It is necessary that in-depth studies are to be carried out to complete the missing chain in the calculation of the CVSCs for calculating the weighting matrices.

Another point in considering the study by McGranaghan and Roettger [26] is that during the analysis, the voltage sags were compared to the momentary interruptions only. The equivalent damages were proposed accordingly. However, based on IEEE standard 1159–2009 [1] it is known that the duration of voltage sags (0.5 cycles–1 min) covers both momentary (0.5 cycles–3 s) and temporary interruptions (3 s–1 min). These observations necessitate the calculation of a new equivalence factor matrix which will form a link between economic losses of voltage sags and short interruptions (momentary and temporary). Moreover, for the sake of reaching more customer specific evaluations, unique equivalence factor matrices are needed for each industry subsector. This step is a highly challenging one to complete since it requires additional extensive customer surveys and calculations. Therefore, this challenge has been left open for future studies.

2.3. Customer Voltage Sag Costs

After following the block diagram presented in Figure 1, the CVSC estimation for a single event can be formulated as follows:

$$\mathrm{CVSC}\ (\mathrm{s}) = \frac{\mathrm{VA(s)}}{\mathrm{w(s)h} \times 3600}\mathrm{K(s)\ t\ E(s)} \quad (6)$$

where:

CVSC(s): Customer Voltage Sag Cost per sector in €/kWh;
VA(s): annual Value Added per sector in €;
w(s): annual energy consumption per sector in kWh;
h: annual working hours for industry sector;
K(s): weighting factor for 1 s interruption per sector;
t: interruption duration due to the voltage sags in seconds;
E(s): equivalence factor for per sector.

The equivalence factor matrix can be modeled by paying attention to the characteristic of the voltage sag. The economic damage of each sag event with a different RMS voltage drop will be equal to that of an interruption multiplied by a unique factor (see Table 6).

Table 6. Equivalence Factor Matrix.

Voltage Magnitude	Equivalence Factor (E)
100%	0
90%–70%	a
70%–50%	b
50%–10%	c
<10%	1.0

Note: The values for a, b, and c are just random symbols.

The true equivalence factor values differ by the varying voltage magnitude and they are to be calculated separately for each industry sectors. To calculate the total voltage sag losses in a year, (6) can be modified as:

$$\mathrm{CVSC}\ (s) = \frac{\mathrm{VA}(s)}{w(s)h \times 3600} K(s) \sum_{i=0}^{n} t_i E_i(s) \tag{7}$$

where n is number of sag events in a year.

By considering that in a customer segment there could be hundreds of sag events in a year, it will be difficult and time consuming to follow (7) and calculate the CVSCs. Therefore, if a more straightforward and plain model is needed, with the aid of voltage sag tables and voltage sag indices, (7) can be further simplified. A voltage sag table is a commonly used tool to assess the performance of a site. The rows of the table denote the retained RMS voltages and the columns represent the sag durations. A typical example can be found at the IEC 61000-2-8 [29]. Nevertheless, monitoring and measuring the voltage sag events is a tedious job. Therefore, as it is the main objective of this paper, it is more convenient to follow and focus on outage events and their durations resulting from the voltage sags.

System Average RMS Variation Frequency Index (SARFI) is a PQ index which gives the rate of sags, swells, and/or interruptions for a period of time. SARFI-X corresponds to a count or rate of these events below or above a voltage threshold. The threshold is designated by the subscript x. For example, SARFI_{60} counts voltage sags and interruptions that are below the threshold of 60% of the reference voltage. SARFI is calculated as follows:

$$\mathrm{SARFIx} = \sum \frac{\mathrm{Ni}}{\mathrm{Nt}} \tag{8}$$

where x is the percentage of the nominal rms voltage; Ni is the number of customers experiencing voltage deviations; Nt is the total number of customers served.

Since one of the main purposes of this paper is to highlight the link between voltage sags and power interruptions, it will be beneficial to make an analogy between interruption and sag indices. It is clear that by denoting the frequency of events SARFI and System Average Interruption Frequency Index (SAIFI) indices are related to each other. However, during the CIC assessment studies, instead of SAIFI, System Average Interruption Duration Index (SAIDI) is more useful. Nevertheless, a widely accepted sag duration quality index standard has not been introduced yet. In light of this fact, by following the same logic with SARFI, a System Average RMS Variation Duration Index (SARDI) can be proposed. The calculation of SARDI-X will be in the same manner:

$$\mathrm{SARDIx} = \sum \frac{\mathrm{di}}{\mathrm{Nt}} \tag{9}$$

where x is the percentage of the nominal RMS voltage; di is the duration of interruption resulted by the voltage sags; Nt is the total number of customers served.

Annual $SARDI_x$ values can be calculated via the voltage sag tables. The unit will be in seconds. In considering this, (7) can be transformed as:

$$\mathrm{CVSC\ (s)} = \frac{\mathrm{VA(s)}}{\mathrm{w(s)h} \times 3600}\mathrm{K(s)}\sum_{\mathrm{i=1}}^{8}\mathrm{SARDI(s)}_{10(\mathrm{i}+1)-10\mathrm{i}}\ \mathrm{E(s)}_{10(\mathrm{i}+1)-10\mathrm{i}} \quad (10)$$

where $SARDI_{10(i+1)-10i}$ is the SARDI seconds between a sag threshold voltage. For example, $SARDI_{90\text{-}80}$ is the annual interruption duration due to voltage sags which are between sag thresholds of 90% and 80% RMS voltages. At this point a more detailed equivalence factor matrix is needed. The matrix is shown in Table 7.

Table 7. Equivalence Factors.

Retained Voltage V (%)	Equivalence Factor (E)
80% < V ≤ 90%	
70% < V ≤ 80%	
60% < V ≤ 70%	
50% < V ≤ 60%	
40% < V ≤ 50%	
30% < V ≤ 40%	
20% < V ≤ 30%	
10% < V ≤ 20%	
V ≤ 10%	

Equation (10) is a novel macroeconomic approach that estimates the total economic losses of voltage sags in a year. The resulting figures are meaningful in terms of being sector specific. The model enables the utilities, the power system planners, and the authorities to calculate the value of electric power reliability, in particular the CVSC, in a simple and straightforward manner. The methodology makes use of publicly available and objective analytical data such as value added, annual energy consumption, and working hours. In addition to these, customer specific data for weighting and equivalence factors are included in the analysis process.

2.4. Case Studies

During the customer survey mentioned in [23], within the food sector customers F_1 and F_2 reported the following figures:

Customer F_1: annual value added: 1,200,000 €, reported cost for 1 h outage: 1500 €

Customer F_2: annual value added: 5,300,000 €, reported cost for 1 h outage: 3000 €

By following (3) and considering that K(food) = 1.96 for 1 h of unexpected outage, the following calculations can be made:

$$CIC(F1) = \frac{1{,}200{,}000\text{ €} \times 1\ h}{3000\ h}1.96 = 784\text{ €} \quad (11)$$

$$CIC(F2) = \frac{5{,}300{,}000\text{ €} \times 1\ h}{3000\ h}1.96 = 3463\text{ €} \quad (12)$$

According to the study done by Leonardo Energy [9], the cost of power quality events in Europe exceeds 150 billion euros annually. The industry sector PQ loss figures correspond to almost 5% of the European Union (EU) industry sector GDP. This argument seems to be overestimated since a 5% loss is unreasonably high. reference study by LaCommare and Eto [25] estimated the total costs of power outages to the US economy to be around 79 billion dollars during the year 2004. This figure covers all of the US economy, not just the industry sector. On the other hand, it is well known that electric power reliability is higher in Europe than in the United States. For example, during 2013 the annual average power outage was less than 3 h in the EU [30] while it was higher than 3 h in the U. [31]. LaCommare and Eto [25] also reported that the estimated costs could be as high as 135 billion or as low as 22 billion dollars based on the sensitivity assumptions. This is a clear example of getting extremely high error margins if one attempts to make macro level cost estimations. One of the main motivations behind the macroeconomic model (10) is to reduce these large error margins via reducing the level of customer survey dependence during the analysis process. It should be highlighted that due to risk aversion behavior, customers tend to exaggerate their losses when they answer the survey questionnaires [32].

Let us take customer F_2 as an example and suggest the following hypothetical voltage sag performance scenario with Table 8 to perform (10). On the table, the outage duration stands for the annual outage time of production due to voltage sags.

Table 8. Hypothetical Voltage Sag Performance Table of Customer F_2.

Retained Voltage V (%)	Outage Duration (s)	Equivalence Factor (E)
80% < V ≤ 90%	2 000	0.1
70% < V ≤ 80%	1 500	0.3
60% < V ≤ 70%	1 400	0.5
50% < V ≤ 60%	1 300	0.8
40% < V ≤ 50%	1 200	0.9
30% < V ≤ 40%	1 100	1.0
20% < V ≤ 30%	1 000	1.0
10% < V ≤ 20%	900	1.0
V ≤ 10%	800	1.0

The annual energy consumption of F_2 is 1,781,880 kWh, the annual working time is 3000 h and K(food) is 1.93 for 1 s. Then;

$$\begin{aligned} CVSC(F2) = {} & \frac{5{,}300{,}000\ €}{1{,}781{,}880\ \text{kWh} \times 3000 \times 3600\ s} 1.93[(2000 \times 0.1) + (1500 \times 0.3) + (1400 \times 0.5) \\ & +(1300 \times 0.8) + (1200 \times 0.9) + (1100 \times 1.0) + (1000 \times 1.0) + (900 \times 1.0)]s \end{aligned} \tag{13}$$

$$CVSC(F2) = 0.35\ €\ \text{cents/kWh} \tag{14}$$

As such, in monetary terms, the cost of voltage sags in a year will be approximately 6200 €.

The above CVSC calculation is an example showing the application of (10). In order to reach actual estimations, Voltage Sag Tables and Equivalence Matrices have to be prepared for each industry sector. Carrying out sensitive power quality measurements at the customer's side is a must for achieving this goal.

3. Discussion and Conclusions

Voltage sags might not be a big problem for residential consumers, however, it is evident that these events pose significant economic threats to industrial customers. Targosz and Manson [9] state that the PQ losses of the industry sector constitute around 90% of the total costs of all sectors included in the survey. Voltage sags and short interruptions alone are responsible for more than 50% of the total losses. This finding is sufficient for understanding the significance of the electric power reliability especially for industrial sector customers. Another conclusion could be that a correlation must be established between the consequences of voltage sags and short interruptions. It is vital to define the equivalent economic damage of a certain sag event to that of a short interruption.

Proposing a stochastic or a probabilistic estimation method for assessing the costs of voltage sags might address one single customer or even one particular manufacturing process. On the other hand, finding the relationship between the operation of the whole process and hence the system performance of a customer and the performance of each individual component is a very difficult task. Although there are some methods that can be used to achieve this task, such as process flow charts, functional block diagrams, or fault tree analysis, proposing the same methodology for all consumers in a consumer segment is technically impossible. That is why there is a crucial need for approaching the phenomenon with a macro perspective so that the recommended model can easily be utilized for a larger number of customers. That is why a macroeconomic model is vital for all participants of the electric power business. On the other hand, the recommended model should be as customer specific as possible. Suggesting the use of the same model for all industry subsectors will create average and therefore unreliable estimations. For example, the voltage sag susceptibility and hence the resulting economic losses of the construction sector and pharmaceuticals sector are not the same. This observation constitutes one of the strengths of the macroeconomic model presented in this paper. The elements of K(s) and E(s) are sector specific. This means unique weighting and equivalence coefficients are needed for each industry subsector.

One question regarding the voltage sags is whether the value of a voltage sag is time varying or not. Even though the value of energy fluctuates in accordance with the daily load curve and other market dynamics, during working hours the value of continuity of supply is constant for the industry sector's customers. For example, for an electronics manufacturing customer a momentary interruption at 10 a.m. and the same event at 3 p.m. will not cause considerably different amounts of economic losses since the cost types presented in Section A are not working-time dependent. That is why the macroeconomic model (10) omits the characteristics of the time at which the power quality event takes place.

In order to finalize the macroeconomic model for estimating CVSCs, the correlation between voltage sags and short interruptions must be found. After that, corresponding equivalence factor matrices can be prepared for different voltage sag magnitudes. Since the demands of this task require far too much time and effort, this work has been left as a future study by the authors.

Author Contributions: Küfeoğlu introduced a novel customer interruption costs estimation model in his previous studies. In this work he proposed the theory of linking the costs of interruptions events and the costs of voltage sags. He carried out the analysis work to justify the theory. Lehtonen contributed to the research work by highlighting the tripping behavior of voltage sags in industrial processes and hence the nature of these events in causing monetary losses.

Conflicts of Interest: The authors declare no conflict of interest.

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