Determining Optimal Custom Power Devices to Enhance Power Quality

Dong-Jun Won† and Seung-Il Moon*

Abstract - This paper proposes a novel method for determining the kind and rating of power quality solutions. To determine the kind of solution, event cause and direction are utilized. According to the event cause and direction, an adequate type of solution is determined for effective compensation. To rate the required capacity of solution, the concept of lost energy is adopted. Lost voltage, lost power and lost energy are calculated and the rating of the solution is determined to compensate a specific event. The rating method that utilizes the result of stochastic diagnosis is also proposed. A power quality index such as CP95 is adopted for solution suggestion. The method developed in this paper is applied to the test system and proved to be useful for enhancing the power quality of the customer system. It can provide customers with information pertaining to what is a proper and cost-effective solution among various compensating devices.

Keywords: custom power device, CP95, diagnosis, harmonics, power quality, UPQC, voltage sag

1. Introduction

Power quality (PQ) management includes power quality monitoring, power quality diagnosing and power quality solving. Power quality monitoring detects the power quality events and collects the data of a power system. Power quality diagnosing interprets the data and changes them into valuable information for customers to be able to understand their power quality. Power quality solving finally enhances the power quality of the customer power system. These three steps complete the management of customer power quality. If the investment for power quality management is insufficient, the damages from power quality problems increase. On the contrary, if the investment is excessive, the damages decrease but the total cost can increase [1]. Therefore, it is necessary to determine the optimal investment for power quality management.

The final goal of power quality management is to enhance the power quality level of the system. For this, power quality problems that damage the customer equipment must be solved by appropriate solutions. In order to solve power quality problems, the most commonly used solutions are custom power devices. Because there are various types of custom power devices according to power quality events, selecting the appropriate kind of custom power device is imperative. Furthermore, because the custom power device is installed in front of the related component to compensate the power quality, the size of solution must be accurately rated. Therefore, the determination of adequate kind and rating of the power quality solution is fairly important to customers. The customer will refer to the suggested solutions for economic efficiency.

In this paper, a novel method for determining the kind and rating of power quality solutions is proposed. To determine the kind of solution, event cause and direction are utilized. To rate the required capacity of solution, the concept of lost energy is adopted. Lost voltage, lost power and lost energy are calculated and suggested for appropriate solution of a specific event. The rating method that utilizes the result of stochastic diagnosis is also proposed. A power quality index such as CP95 is adopted for solution suggestion. The method developed in this paper is applied to the test system and shows that the power quality solution rated and positioned appropriately can improve power quality.

2. The Kinds of Solution

2.1 Classification of Custom Power Device

Custom power devices can be classified into two major categories [2]. One is network configuring type and the other is compensating type. The former changes the configuration of the power system network for power quality enhancement. SSCL (Solid State Current Limiter), SSCB (Solid State Circuit Breaker) and SSTS (Solid State Transfer Switch) are the most representative in this category. SSCL inserts an inductor in series with a power system and limits the fault current. SSCB acts as a

† Corresponding Author: Advanced Power Technologies Center, Department of Electrical Engineering, University of Washington, Seattle, WA 98195-2500 USA. (dwon@ee.washington.edu)
* School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea. (moonsi@plaza.snu.ac.kr)
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protection device. It isolates the faulted circuit from the system. It can be thought of as an electrical version of the mechanical circuit breaker. SSTS performs rapid transfer of the load from a faulted line to an alternative line to protect a sensitive load. All of these devices use GTO or thyrister. Therefore, 'solid state' is attached in the name of each device.

The other type of custom power device, that is, the compensating type, consists of DSATACOM (Distribution STATic COMpensator), DVR (Dynamic Voltage Restorer) and UPQC (Unified Power Quality Conditioner). DSTATCOM has a similar structure and function to STATCOM in the transmission system. DSTATCOM is connected in shunt with the power system. DVR is a series connected device that injects a rapid series voltage to compensate the supply voltage. UPQC has a structure similar to that of the UPFC. It injects series voltage and shunt current to the system. The classification of custom power devices according to their type and structure is summarized in Table 1.

Table 1 Classification of custom power devices according to type and connection

Type \ Connection	Shunt	Series	Series & Shunt	Parallel line
Network configuration type	-	SSSL, SSCB	-	SSTS
Compensating type	DSTAT COM	DVR	UPQC	-

2.2 Determination of Solution Kind According to Event Cause and Direction

To determine the kind of power quality solution, the type and cause of power quality event must be identified first. The kind of event is largely classified as voltage variation event and harmonic event. The causes of voltage variation event can be classified as line fault, induction motor starting and transformer saturation. The causes of harmonic event can be classified as 6 pulse converter, 12 pulse converter and other nonlinear loads. Using these results, the adequate type of power quality solution can be proposed.

As well as the event cause, event direction is also utilized in choosing the appropriate kind of solution. The power quality solutions are commonly installed in front of important load to compensate power quality of the load. In addition, power quality monitors tend to be positioned in front of the load. Therefore, it is reasonable to use the event direction of a monitor when the kind of solution is selected among many custom power devices. If a monitor has determined a *DOWN* event [3, 4] and line fault, a large amount of current flows. In this case, rapid current limiting or disconnecting action is required, and SSSL or SSCB is the adequate solution. Induction motor starting and transformer saturation are similar to the case of line fault. In case of *UP* event of voltage variation, it needs not limit current or drop the line as line fault. Only the voltage restoration or change of power source is necessary for *UP* event. Therefore, DVR or SSTS is required. For induction motor starting and transformer event having some kind of harmonic content, UPQC or DSTACOM is more appropriate for filtering. In the case of harmonic event, the solutions are summarized as UPQC or DSTATCOM regardless of the event cause. The kind of power quality solutions according to the cause and direction of power quality event are summarized in Table 2.

Table 2 Suggestion of custom power devices according to event cause and direction

Event Cause \ Event direction		DOWN	UP
Voltage variation event	Line fault	SSSL, SSCB	DVR, SSTS
	Induction motor starting	SSSL	UPQC, SSTS
	Transformer saturation	SSSL	UPQC, DSTATCOM
Harmonic event	6 pulse converter switching	DSTATCOM	DSTATCOM
	12 pulse converter switching	DSTATCOM	DSTATCOM
	Other nonlinear loads	UPQC	UPQC

3. The Rating of Solution

The rating of power quality solution is related to the lost energy during the event. For example, if the total lost energy during the event is about 1 kVAh, then the appropriate rating of solution must be larger than the lost energy. Lost energy can be calculated from the voltage and current during the event.

The power quality solutions are commonly installed in front of important loads to compensate power quality of the load. In addition, power quality monitors tend to be positioned in front of the load. Therefore, it is reasonable that the rating is calculated at the monitor that detects the *UP* event. Using the values at the monitor, the lost energy is computed as follows [5, 6].

$$W = \int \left\{ 1 - \left(\frac{V_{sag}}{V_{rated}} \right) \right\}^{3.14} dt \qquad (1)$$

where,

V_{sag} : *voltage magnitude during voltage sag*

V_{rated} : *rated voltage at the load terminal*

The power of voltage, 3.14, has been calculated from the curve fitting of the CBEMA (Computer Business Equipment Manufacturers Association) curve [7]. Lost energy is calculated from the magnitude and duration of voltage sag event, which are the stored values in the power quality database. The rating of power quality solution is computed by slight modification (1). Because the waveform data of voltage and current have also been stored along with the voltage magnitude and duration, the current is utilized to calculate the lost energy during the event.

$$E_{Lost} = (S_{ss} - S_{\min}) \times t \qquad (2)$$

$$V_{Lost} = V_{ss} - V_{\min} \qquad (3)$$

$$S_{ss} = V_{ss} \times I_{ss} \qquad (4)$$

$$S_{\min} = \min_{n=1,2,\ldots,L} \left\{ \sum_{k=a,b,c,0} (V_{rms}^{\ k}(n) \times I_{rms}^{\ k}(n)) \right\} \qquad (5)$$

where,

S_{ss} : *steady state apparent power*

$S_{\min}$: *minimum apparent power during voltage sag*

V_{ss} : *steady state RMS voltage*

$V_{\min}$: *minimum voltage during voltage sag*

I_{ss} : *steady state RMS current*

k : phases (k=a, b, c, 0)

n : samples (n=1, 2, ..., L)

$V_{rms}^{\ k}(n)$: *RMS voltage at phase k and n^{th} sample*

$I_{rms}^{\ k}(n)$: *RMS current at phase k and n^{th} sample*

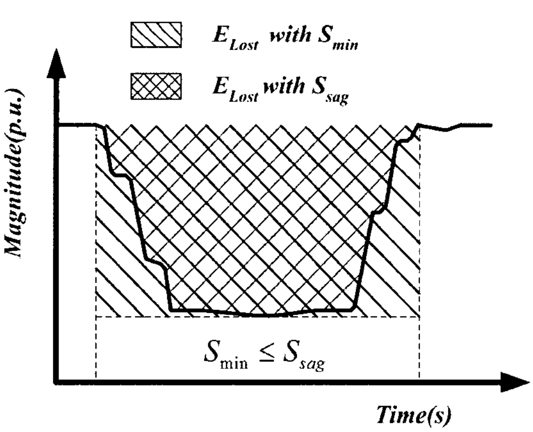

Fig. 1 Comparison of $S_{\min}$ and S_{sag} in calculating E_{Lost}

(2~5) use the voltage, current and duration during voltage sag and their steady state values. The lost energy E_{lost} gives a conservative rating of power quality solution because $S_{\min}$ has been used instead of

$$S_{sag} = \frac{1}{L} \sum_{n=1}^{L} \left\{ \sum_{k=a,b,c,0} (V_{rms}^{\ k}(n) \times I_{rms}^{\ k}(n)) \right\}$$ in (2).

4. Determining the Rating of Solution with Stochastic Analysis

In Chapter 3, the rating of power quality solution for a specific event is discussed. In this chapter, the method on the rating of solution using the historical results of the total events is proposed.

In the power quality diagnosis system, the total events are analyzed together. The trends and statistics of total events are produced for more comprehensive understanding. In stochastic diagnosis, the voltage variation event and harmonic event are analyzed and their characteristics are represented using probabilistic and stochastic analysis. Stochastic diagnosis can also be used in the rating of the power quality solution, especially the 'CP95', which means that 95% of cumulative probability has been used for estimation of the level of harmonic distortion [8]. In this paper, CP95 is extended for the rating of solutions. Compensation of the CP95 value using power quality solution means that the solution can compensate 95% of the total event. For voltage variation event, CP95 is applied to the voltage sag database and the lost energy is computed at every event. After that, the lost energy is sorted by its magnitude and the CP95 of voltage sag is found. For a harmonic event, CP95 is applied to the harmonic event database and the THD is used instead of lost energy. Fig. 2 presents the cumulative chart of a harmonic event. In this figure, the CP95 of the harmonic event is computed as 7.72%.

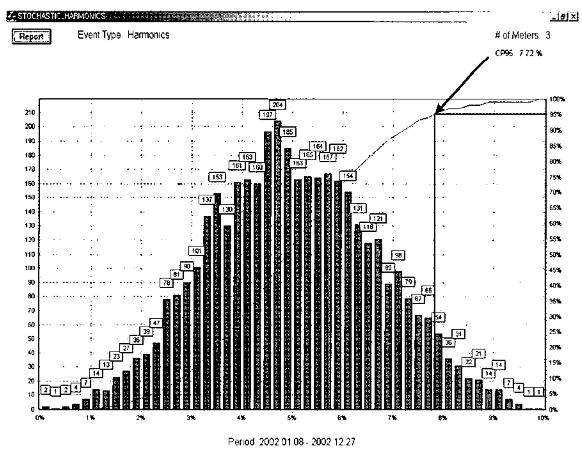

Fig. 2 CP95 of harmonic event for power quality solution

Fig. 3 represents the algorithm to rate the power quality solution with stochastic diagnosis. At first, the power quality events are selected from the database and the direction is identified. If the event selected is identified as a DOWN event, it is not necessary to rate the power quality solution. In this case, the network configuration type device is essential. If the event is identified as an UP event, the rating of solution is performed. This algorithm proceeds until all the events are investigated. At last, the CP95 is computed and an appropriate rating of solution is determined.

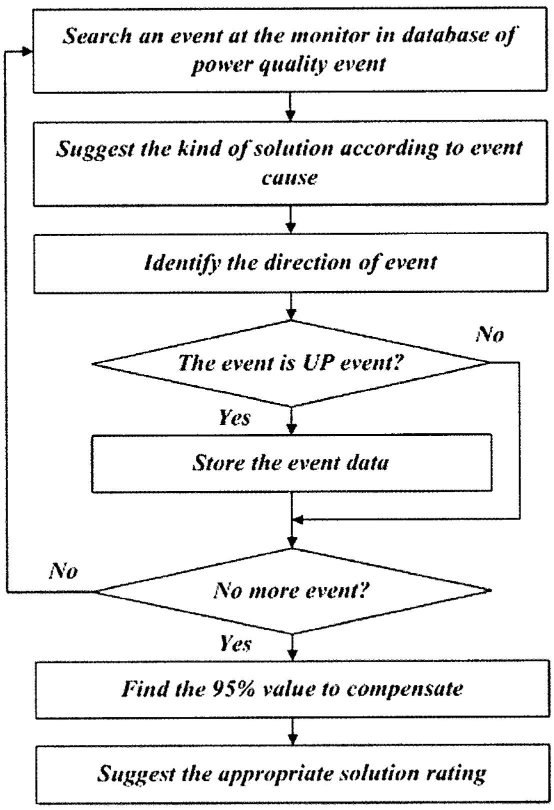

Fig. 3 Solution suggestion algorithm with stochastic diagnosis

5. Application

The solution rating method is applied to the test system shown in Fig. 4. UPQC, one of custom power devices, is installed in the system to enhance the power quality of the special load. UPQC is a series and shunt connected to the test system and controlled by PWM inverters. In the system, there are many kinds of event sources such as inverters and induction motors. For the test, a 3 line to ground fault happens at the indicated location, and voltage sag occurs in all system buses. If there is no UPQC in the system, the special load will experience the voltage sag as shown in Fig. 5.

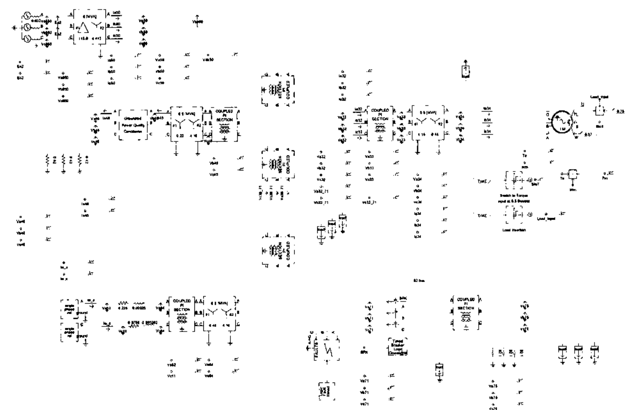

Fig. 4 Test system for solution rating algorithm

Table 3 Fault description

Description / Fault	Kind	Initiate	Duration
Fault	3 line to ground	0.2 sec	0.1 sec

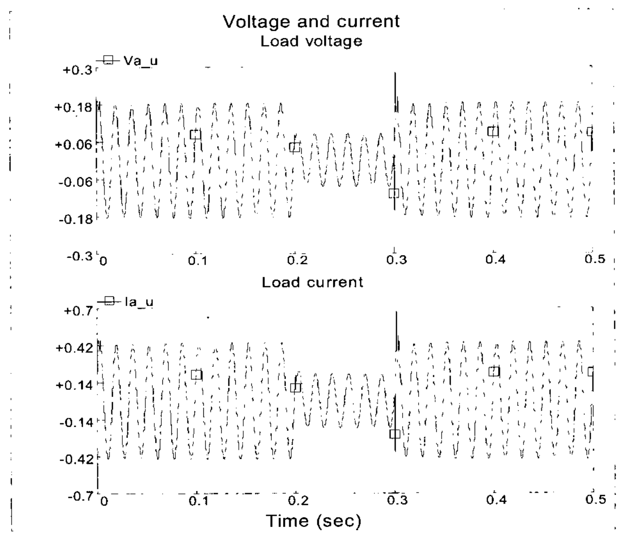

Fig. 5 Load voltage and current without UPQC during voltage sag

The lost energy E_{Lost} due to this fault can be calculated from (2~5).

$$V_{ss} = 0.1322\,kV\ ,\quad I_{ss} = 0.3111\,kA\ ,\quad S_{ss} = 41.4\,kVA\ ,$$
$$S_{\min} = 7.708\,kVA,\ \ t = 0.1\,\sec$$
$$E_{Lost} = 3.34\,kVA\cdot\sec$$

Because the lost energy due to the voltage sag at one phase is calculated as $E_{Lost} = 3.34\,kVA\cdot\sec$, the rating of UPQC must be greater than $E_{Lost,3\phi} = 10.02\,kVA\cdot\sec$. With about 50% margins, UPQC is rated as 15 kVA. Fig. 6 shows the compensation of voltage sag using UPQC.

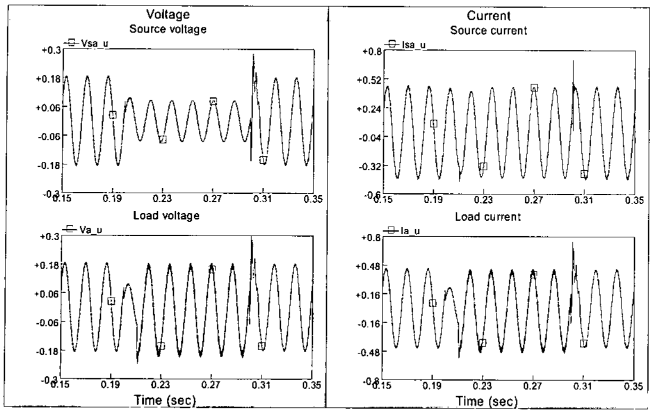

Fig. 6 Effective compensation with proper UPQC rating (15 kVA)

Although the source voltage has voltage sag, the load voltage has no voltage drop with the exception of some transients. This is because the UPQC is properly rated. However, if the rating of UPQC is insufficient to compensate the voltage sag, the load voltage and current will be poorly compensated. Fig. 7 shows the poor compensation of UPQC when the UPQC is improperly rated.

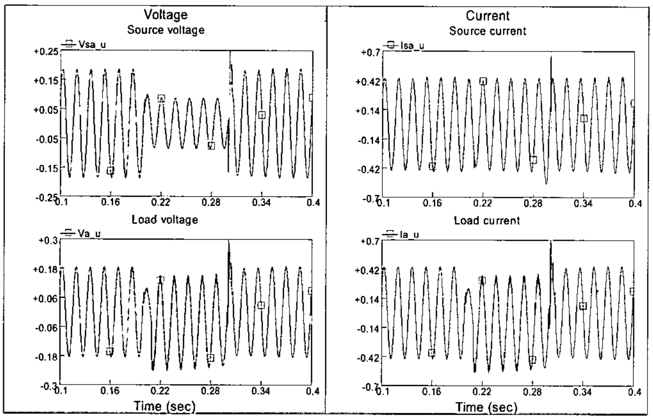

Fig. 7 Poor compensation with insufficient UPQC rating (3 kVA)

As shown in this figure, the rating of power quality solution is a critical factor for effective compensation. The proposed methods on the determination of the kind and rating of power quality solution will provide the customers with information about what is a proper and cost-effective solution among various compensating devices. It is useful in enhancing the power quality of the customer system.

6. Conclusion

In this paper, a method to determine the appropriate power quality solution has been proposed. The kind of solution has been selected from various custom power devices according to the event cause and direction. The rating of solution has been determined from lost energy during a power quality event. It has also been calculated in terms of stochastic analysis, which results in CP95. Using this value, 95% of power quality problems in the system can be solved. A case study has shown that an appropriate power quality solution can effectively remove power quality problems in a power system. The proposed method will give the customers a guideline for their choice and enhance the level of power quality.

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Dong-Jun Won
He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University, Seoul, Korea in 1998, 2000 and 2004 respectively. Previously, he was a Research Engineer at the Engineering Research Institute, Seoul National University. He is currently a Post-doctoral Fellow at APT Center, University of Washington. His special fields of interest include power quality, dispersed generation and hydrogen economy.

Seung-Il Moon
He received his B.S. degree in Electrical Engineering from Seoul National University, Seoul, Korea in 1985. He received his M.S. and Ph. D. degrees in Electrical Engineering from Ohio State University in 1989 and 1993, respectively. Currently, he is an Associate Professor in the School of Electrical Engineering and Computer Science at Seoul National University. His special fields of interest include power quality, FACTS, renewable energy and dispersed generation.