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Novel expert system for defining power quality compensators

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ABSTRACT

In order to ensure good power quality for modern power systems and/or industrial installations, power conditioning devices have been extensively applied. However, the data analysis for the installation of a determined compensator mainly considers a particular power quality index or disturbance and it is usually based on human expertise. Therefore, this paper proposes a novel expert system that automatically suggests the most appropriate and cost-effective solution for compensating reactive, harmonic and unbalanced current through a careful analysis of several power quality indices and some grid characteristics. Such an expert system is an important tool in real-world applications, where there is a complex scenario in choosing, designing and applying power quality compensators in modern power grids. Since there are no strict boundaries for voltage and current non idealities at distribution level or clear correlation between them and possible solutions, a fuzzy decision-maker was developed to deal with such uncertainties and to embed human expertise in the system. The approach is based on analyzing data from a given time window and providing off-line recommendations for the design and installation of proper compensators. Therefore, the application of the proposed expert system may result in enhanced and faster projects when compared to the traditional design methods for power conditioning. A computational study consisting on applying the suggested compensators for a 5-node network and different load configurations shows the effectiveness of the proposed expert system.

1. Introduction

In terms of industrial applications, power conditioning devices may ensure good power quality (PQ) at a certain point of common coupling (PCC). This consists in avoiding that particular load characteristic, such as unbalanced connection, reactive power and non linearities (which cause harmonic distortion) affect the grid. Consequently, the installation of a compensator may increase the network efficiency, reduce costs and avoid consumer's penalizations by low power factor (Akagi, Watanabe, & Aredes, 2007; Bollen, 2003; Singh, Al-Haddad, & Chandra, 1999).

Even though many traditional compensators (such as capacitor banks for power factor correction) are still used and might be cost-effective, there are an increasing number of restrictions for their application, mainly due to high levels of voltage distortion in the grid (Bisanovic, Hajro, & Samardzic, 2014; Jintakosonwit, Srianthumrong, & Jintagosonwit, 2007). In this case, the compensators may cause more problems than tangible benefits (Currence, Plizga, & Nelson, 1995; Obulesu, Reddy, & Kusumalatha, 2014; Phipps, Nelson, & Sen, 1994).

Therefore, during the design stage of a compensation system, it is important to consider several PQ indices, observing its recommended limits (when available), in order to determine the feasibility of such solution.

Nevertheless, the main problems to proceed in this way are: the absence of PQ indices in standard power meters (usual frontier equipment between industries and utilities) and/or contradictory results for a PQ index when calculated by different power meters (Galvão, Belchior, Silveira, & Ribeiro, 2014); the lack of strict boundaries for all voltage and current non idealities at distribution level and specially, the absence of clear relationship among them and possible solutions; and finally, the lack of expertise on the application of power conditioners by young practical engineers.

Regarding the PQ monitoring, the current literature has leading to new trends in electrical grids, mostly related to the concept of

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smart grids and distributed generation systems. In this scenario, the proposed power meters have been named "smart meters" (Marafão, Souza, Liberado, Silva, & Paredes, 2013) and they are able to inform PQ indices and relevant information to consumers and utilities. Moreover, smart metering has been applied to PQ monitoring and assessment of grids with distributed renewable sources (Chompoo-Inwai & Mungkornassawakul, 2013; Golovanov, Lazaroiu, & Porumb, 2013; Su et al., 2013; Vallée et al., 2013; Zhang, Yan, Yang, Bao, & Sun, 2013; Hashemi & Aghamohammad, 2013; Yang et al., 2013) and PQ event diagnosis (Faisal, Mohamed, Shareef, & Hussain, 2011; Gunal, Gerek, Ece, & Edizkan, 2009; Kriukov, Grigoras, Scarlatache, Ivanov, & Vicol, 2014; Salem, Mohamed, & Samad, 2010; Wang & Tseng, 2011). In such applications, some PQ indices are calculated, the voltage profile is estimated and the data is properly processed, but the proposed systems just provide information that must be analyzed by end-user in order to make a decision about the need of power conditioning for ensuring pre-defined PQ levels.

In terms of expert systems related to PQ compensators, some recent applications are optimal planning of passive filters (Bhattacharya & Goswami, 2009; Chang, 2010; Chang, Low, & Hung, 2009; Low, Chang, & Hung, 2009) and control of FACTS (Flexible AC Transmission Systems) (Banerjee, Mukherjee, & Ghoshal, 2014; Suslov, Solonina, & Smirnov, 2014) and inverters (Cheng, 2011; Jegathesan & Jerome, 2011; Ray, Chatterjee, & Goswami, 2010; Tutkun, 2010). However, those authors are focused on a particular sort of compensators and, predominantly, considering the PQ indices related to harmonic distortion.

On the other hand, expert systems have been extensively applied in industrial and power systems, power electronics and related areas, as well as revised by Hassan, Moghavvemi, Almurib, and Steinmayer (2013) and Sahin, Tolun, and Hassanpour (2012). Additionally, a related application of expert systems that should be highlighted is the definition of new PQ factors based on the ones traditionally used to quantify the PQ (Arghandeh, von Meier, & Broadwater, 2014; Morsi & El-Hawary, 2008a,b).

Therefore, this work proposes an expert system that calculates relevant PQ indices in order to characterize the most significant ones, analyses those PQ indices and, as a result for the end-user, defines a proper PQ compensator to improve the PQ on a particular point of common coupling (PCC).

On the proposed approach, the decision process is found on a Fuzzy Decision-Maker (DM) (Bellman & Zadeh, 1970; Caia, Huangc, Lina, Niea, & Tana, 2009; Piltan, Mehmanchi, & Ghaderi, 2012), which is typically used when the expected output is a list of linguistic alternatives (decisions) and the defuzzification is not applicable or necessary. Thus, this fuzzy decision process is responsible for correlating PQ indices and grid characteristics through a Fuzzy Rule-Based System (FRBS) towards representing the human expertise in compensation technologies. The decision-maker is based on off-line analysis of previously measured data, within a given time window.

The next sections describe the adopted PQ indices and grid characteristics, the proposed expert system, its application (in simulation) on a grid with different load configurations and the results of installing the suggested compensators for each load condition.

2. Power quality indices and grid characteristics

In order to quantify the power quality at a given PCC, several PQ indices may be calculated and analyzed. Some of them have recommended limits that may be used for utilities to penalize consumers (or loads) that do not respect the predefined bounds.

For the development of the proposed expert system, the authors chose to use indices extracted from IEEE recommendations (IEEE – Institute of Electrical and Electronics Engineers, 1993; IEEE – Institute of Electrical and Electronics Engineers, 2010), which deal with the most important PQ disturbances and might offer useful information to determine proper compensation systems.

Moreover, there are some grid characteristics that might be considered to determine a suitable compensator, such as the short circuit level (SCl) and the dynamic behavior of the fundamental positive sequence reactive power (Q_1^{+}) (IEEE – Institute of Electrical and Electronics Engineers, 2010). These characteristics and the selected PQ indices are described in the following.

2.1. Total harmonic distortion (THD) and total demand distortion (TDD)

The *THD* index (i.e., the ratio between the harmonic components and the fundamental frequency component of voltages or currents) is used to quantify the harmonic distortion of voltages (*THDv*), in order to determine if voltage distortions could damage, e.g., the installation of a capacitor bank.

The limits adopted for *THDv* follows the IEEE 519-1992 (IEEE – Institute of Electrical and Electronics Engineers, 1993), which recommends that for voltage levels under 69 kV the *THDv* should not be bigger than 5%.

In order to determine if harmonic current mitigation is necessary, the total demand distortion (*TDDi*) is adopted (IEEE – Institute of Electrical and Electronics Engineers, 1993), which is the ratio between the harmonic currents and the maximum demand load current.

In fact, the main goal of the harmonic current mitigation is to avoid that the harmonic currents affect the supply voltages through the supply/line impedance. Thus, an important grid characteristic to be considered during the PQ analysis – and is often used by IEEE (1993) to determine the *TDDi* limits – is the short-circuit level (SCl) of the PCC, which is the ratio between the short circuit current (or short circuit apparent power) and the maximum load current/apparent power demand.

In other words, in a grid with high SCl (the so called "strong grid") the current demand is low and the current distortion would not significantly affect the grid, thus in this case the *TDDi* limits are greater than in a PCC with a small SCl (which is called "weak grid"), which is shown in Table 1, extracted from IEEE (1993) for voltages under 69 kV.

2.2. Unbalance factor (K)

The unbalance factors consider fundamental sequence components and may be useful to quantify PCC voltage and current's asymmetries (IEEE – Institute of Electrical and Electronics Engineers, 2010). Eq. (1) presents the negative sequence (K^{-}) and the zero sequence (K^{0}) unbalance factors for a three phase system:

$$KX^{-} = \frac{X_1^{-}}{X_1^{+}} \cdot 100 \quad KX^{0} = \frac{X_1^{0}}{X_1^{+}} .100 \tag{1}$$

on which X_1 is the RMS value of the fundamental positive, negative or zero sequence of voltage or current's signals.

The unbalance factors for the voltages (KV^{-} and KV^{0}) are limited in 2% for voltage levels greater than 13.8 kV. However, for voltage

Table 1
Adopted limits for total demand distortion of currents.

SC1	*TDDi* (%)
<20	5.0
20–50	8.0
50–100	12.0
100–1000	15.0
>1000	20.0