Methodology for Optimized Power Quality Compensation in Networks with Electrified Railways

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Abstract—Electrified railways cause power quality (PQ) issues and different solutions on PQ compensation are studied and analyzed in the past work. However, little of them provide theoretical justification on their selection when making compromise among different PQ indices or between the power quality performance and the cost. This paper investigates an optimized PQ compensation methodology to help selection on PQ compensation based on both overall PQ performance and cost so that the power quality is considerably improved as well as that the cost is reduced. For different buses/areas that need to be compensated, individual PQ indices (e.g., harmonics, unbalance, power factor) are combined into an overall index which indicates the overall PQ performance. Then, based on the overall PQ index and the cost function, the most suitable way of compensation is given. The methodology is implemented in a power network with electrified railways in Northwest China.

Index Terms—Analytical hierarchy process, electrified railway, optimized compensation, overall power quality index.

I. INTRODUCTION

Optimized power quality compensation (OPQC) is referred to as power quality compensation way that improves the power quality (PQ) performance and simultaneously remains the cost of PQ improvement within a relatively low range. Electrified railways are widely applied in modern industrialized countries due to the convenience and efficiency they provide. They are typically composed of AC-DC locomotives or AC-DC-AC locomotives. Due to the adoption of power electronic components, harmonics are produced in the network. As locomotives are the single-phase load, negative-sequence current injecting into the grid and affecting power systems is produced. In most cases, locomotives are composed of rectifiers and inverters. As a result, the distortion of the current waveform in AC side as well as the effect of overlapping angle of commutation induce low power factor, about 0.8 to 0.85 [1]. Therefore, harmonics, unbalance and low power factor are the three main power quality issues that need to be handled in power grids with electrified railways.

Significant attention has been paid to power quality compensation of power systems with electrified railways in the past work. Passive filtering and PWMs are widely used to suppress harmonics and improve power quality [2-6]. In [3], a passive filter compensator with a single-tuned filter and a 2nd-order high-pass filter is designed to reduce the harmonics. The former was designed to eliminate the low-order harmonics and compensate reactive power, and the latter was used to suppress the high-order harmonics and harmonic resonance. Similarly, a resonant harmonic elimination PWM method is developed in [5] to mitigate resonant harmonics in the harmonic source of an autotransformer fed electrified railway. However, research listed above considers only harmonics. Therefore, some other methodologies have been used to simultaneously compensate for the harmonics, negative-sequence current and power factor or a subset of them.

In [6], a hybrid shunt compensation system consisting of a cascaded or reduced topology multilevel active power filter and a low rating passive damping filter is developed to improve traction system power transfer capacity. The active power filter is used for reactive power compensation and low-order harmonic mitigation, and the passive damping filter is used for high frequency oscillation damping. In [7], a railway power conditioner (RPC) with Vx connection traction transformer and active power factor controller are used for power quality improvement. In [4], a novel active power quality compensator (APQC) composed of a three-phase converter and a Scott transformer is developed to improve the power quality of traction system. It showed that the reactive power, harmonics and negative-sequence current in two feeders could be compensated together by using APQC. Nevertheless, according to the comparison in [8], the cost of APQC and RPC is high; therefore in [8], a hybrid traction power quality compensator composed of a five-level full-bridge converter and two static VAR compensators is designed to compromise all power quality problems. The number of IGBTs are reduced from 8 to 6 to reduce the cost. Alternatively, partial compensation can also be used to reduce cost. In [9, 10], the concepts of comprehensive compensation and partial compensation are proposed, and the partial compensation method is developed to compensate the power factor to 0.9 or 0.95 instead of one to reduce the rating as well as the cost of RPC. In these cases however, the effect of partial compensation in power factor is not as good as that in comprehensive compensation where the unity power factor is reached.

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From the literature review above, it can be seen that different compensation ways compensate for different PQ issues and have different functionalities, and selections should be made based on different operation scenario to simultaneously solve PQ issues and reduce cost as much as possible. However, little of the past work has provided a methodology to make such a selection and justify it. This paper investigates an optimized PQ compensation methodology to provide suggestions on PQ compensation methodology selection based on both overall PQ performance and cost in different cases so that the power quality is considerably improved as well as that the cost is acceptable. At beginning, for different areas that need compensation, individual PQ indices (e.g., harmonics, unbalance, power factor) are combined into an overall index which indicates the overall PQ performance. Then, based on the overall PQ index, buses which need to be compensated in priority is judged. Finally, based on the judgement and the cost function, the most suitable method for compensation is suggested. The methodology is implemented on a 124-bus network built from part of the Northwest Power Grid in China.

II. OVERALL POWER QUALITY PERFORMANCE AND ANALYTIC HIERARCHY PROCESS

A. Overall Power Quality Performance

The power quality performance of a power system is determined by a number of individual indices such as harmonics, unbalance, power factor, etc. In other words, all indices above should be considered in assessment of power quality performance, which complicates the process of assessment. Therefore, a terminology named overall power quality index is proposed to simplify the assessment process and visualize power system performance at different areas in a system. It is defined as an index (always represented by a number) which is calculated from different individual indices.

A variety of methodologies are used for overall power quality index derivation in the past work, such as averaging, machine learning, fuzzy logics, analytic hierarchy process (AHP) [11, 12]. Due to the ability of AHP in handling complicated decision making problems, it is adopted in this paper to illustrate the process.

B. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a mathematical model for handling decision making problems with multiple criteria. It combines different criteria into an overall index to enhance objective decision making. An example of overall power quality index (OPQI) calculation is given in Fig. 1. As shown in Fig. 1, the model contains three levels. Level 1 is the goal level, in which the overall score is calculated and defined as OPQI. Level 2 is the selection criteria, including harmonics, unbalance and power factor, each of which has a pre-defined weight for final selection. Level 3 is the level of alternatives. In this level, a standard for performance on different individual criteria and a rule for judgement are given, and the actual performance of each criteria will be scored based on the standard. For example, total harmonic distortion (THD) is used to assess the performance in criteria “harmonics” and THD should not exceed 4%, then the standard could be given by a piecewise function as follows: If THD is smaller than or equal to 4%, the score may be given by a linear function from 100 to 90; otherwise, the score could be given by another linear function which dramatically decrease from 90 to 0 at some point, e.g., 12%. In this case, a higher score indicates better performance of power quality, and areas or buses with lower scores should be compensated in priority, especially under the circumstances that the money, labor or time can support only a restricted number of compensator installation. Sometimes, OPQI can represents the pollution index of harmonics or unbalance factor; in this case, a higher score indicates worse performance and areas or buses with higher scores are in priority for compensation.

\[ OPQI = \sum_{i=1}^{N} w_i S_i \]  

(1)

where \( w_i \) represents the weighting factors of different individual criteria, and \( S_i \) represents the score of individual criteria. The weighting factors of individual criteria are determined based on the sensitivity of the bus to different criteria and it varies in different cases. Determination of weighting factors is another research area and will not be discussed in this paper.

III. OVERALL FRAMEWORK

The overall framework for optimized power quality compensation is shown as Fig. 2. The procedures for optimized power quality compensation are as follows: i) At the beginning, the models of electrified railways and the network are built in advanced digital power system simulator (ADPSS), and total harmonic distortion (THD), current unbalance factor (IUF) and power factor (pf) of all buses that need to be compensated are derived from the voltage, current, real power and reactive power waveform. In this paper, current unbalance factor (IUF) is defined as

\[ IUF = \frac{I_2}{I_1} \times 100\% \]  

(2)

where \( I_2 \) represents the negative sequence current, \( I_1 \) represents the positive sequence current, and the ideal value of IUF in a balanced system should be 0; ii) using AHP, OPQI of each bus is calculated; iii) \( N \) in Fig. 2 represents the maximum number
of compensators to be installed, and \( n \) represents the total number of buses that need to be compensated. If \( n > N \), the \( N \) buses in priority would be selected from the \( n \) buses based on OPQI, otherwise buses will be compensated as many as possible; iv) considering the compensation effect and the total cost for compensating all buses, optimized compensation methodology will be suggested.

![Block diagram for OPQI derivation using AHP](image)

**IV. NETWORK WITH ELECTRIFIED RAILWAYS**

The network used for implementation of the approach is built based on part of a real power grid in Northwest China. In this paper, advanced digital power system simulator (ADPSS) is used for modeling of the electrified railway and the network where the electrified railways travel.

### A. Model of Electrified Railway

An ADPSS model for a single AC-DC-AC locomotive is shown in Fig. 3. It is mainly composed of a three-winding transformer, a pair of rectifiers and inverters, a pair of three-phase asynchronous machines and control systems. The AC-DC-AC locomotive is connected to a 25kV bus with other four locomotives in a traction power supply system.

**B. Model of Traction Power Supply System**

Fig. 4 shows an ADPSS model for a traction power supply system. It is composed of a 230kV traction substation and two traction supply arms, one of which is upstream and the other is downstream. The locomotive can be connected at either the upstream or the downstream side based on the operation scenario in the reality. The traction power supply system (230kV side) is connected to a 230kV bus in a large power network, which is built from part of the real Northwest Grid in China.

![ADPSS model of a traction power supply system with locomotives](image)

**C. Model of Network for Implementation**

A 124-bus network used for implementation is shown in Fig. 5. The network is built from part of the real Northwest Grid in China with electrified railways traveling frequently. Parameters of the network components are provided by the State Grid Dispatch Centre.

![Equivalent network of a part of Northwest Power Grid in China with 124 buses used for implementation](image)

**V. RESULTS AND DISCUSSION**

### A. Individual Power Quality Indices

The harmonic current analysis at the 230kV side under the circumstance of an electrified railway traveling between Phase B and Phase C is given as Fig. 6. It can be seen that harmonics of 3rd, 17th, 19th, 21st, 23rd, 25th, and 29th order are relatively high compared with others, especially the 23rd and the 25th which are caused by resonance. THD of Phase B and phase C are 21.49% and 15.54%, which also indicates an unbalance.
The three-phase current waveform of the 230kV bus is given in Fig. 7. From Fig. 7, an unbalance is visible. The positive and negative sequence current is about 24 and 23A, respectively, and IUF=95.83%. The power factor of the 230kV bus side remains around 1, because the control system is PWM modulated. Therefore, in this case study, the main power quality issues are negative sequence current and harmonics. As a result, the criteria in AHP process are IUF and THD.

With a similar analysis approach as above, in case that electrified railways travel on the 124 buses in the network during the same period, THD and IUF at all buses are derived and plotted in Fig. 8.

According to the experiment result and conclusions in [13] which is conducted for the network in the same area as the network used in this paper, negative sequence current influences more on the network and is more difficult to solved than the harmonics. In this paper, the weighting of THD and IUF for each bus is configured to 40% and 60% to illustrate the process. It is noted that the weighting factor may vary among different buses, depending on the actual operation scenario and bus sensitivity.

1) Selection of Standard for Individual Indices

Based on Fig. 8, it can be observed that before compensation, THD ranges from 95%-97%. The ideal value of THD and IUF are both 0. For convenience, the standard of score for THD and IUF can be made as follows: the scores for both THD and IUF are distributed from 0 to 100 evenly, shown as

\[
S_{THD} = 4 \cdot THD
\]

\[
S_{IUF} = IUF
\]

where \(S_{THD}, S_{IUF}\) is the score for THD and IUF respectively and THD and IUF are in percentage. Lower score indicates better performance.

C. Derivation of OPQI

OPQIs of Bus 1-124 are shown in Fig. 9. It can be seen that with electrified railways, OPQI in the network ranges from 82 to 90 and the solid line shows that the average OPQI for the network is about 86.2. The buses with higher OPQIs, e.g., those above the average line, should be compensated in priority.

D. Optimization

Optimized power quality (PQ) compensation can be formulated to an optimization problem which minimize the average OPQI of the network and the total cost for compensation. The optimization model for optimized PQ compensation is shown as Fig. 10. The dash-dotted line represents the upper and lower bound of OPQI curve clusters and the dashed line represents those of cost curve clusters. The area ABCD with shadow provides feasible selections for optimized PQ compensation.

The procedure of the optimization process to compensate OPQI for a network and to make the total cost as low as possible is as follow: i) re-order the buses by OPQI in descending sequence so that Bus 1 scores the highest and Bus 124 scores the lowest; ii) Start to compensate from the 1st bus and update the average OPQI of the network each time when a
bus is compensated to an OPQI under a specific value (e.g., a number between 0-10); iii) Correspondingly, update the cost upon the OPQI is updated; iv) In ii) and iii), curve clusters of OPQI and cost can be plotted to form two bands and the upper and lower bounds of the two bands can be found, shown as the four curves in Fig. 10; v) With the bounds in iv), shadowed area ABCD can be derived. More constraints such as maximum cost or maximum number of buses to be compensated can further narrow the area and help with discovery of the optimized solutions.

Considering the power quality performance of the 124-bus network with electrified railway and the cost index of the compensation way for different buses under different scenario [13], the optimized compensation plot is given as Fig. 11. The solid lines represent the upper and lower level of the cost curve clusters, and the dot lines represent those of OPQI curve clusters. The closed quadrilateral area represents the range feasible for selection of optimized power quality compensation which simultaneously minimize the OPQI and the cost. It can be observed that the optimized number of buses to be compensated out of the total number (i.e., 124) ranges from 58 to 77, depending on further constraints of OPQI, cost and number of buses to be compensated.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, an optimized power quality compensation methodology is used to improve the overall power quality performance as well as to reduce the cost for power quality compensation. At beginning, models of the electrified railways, the traction power supply system and the network where electrified railways travel frequently are built in ADPSS. Based on the model, power quality indices including harmonics, unbalance and power factor are analyzed and individual indices used for this study are determined. Then, analytic hierarchy process (AHP) is used to derive OPQI of different buses from THD and IUF. OPQI indicates overall power quality (PQ) performance of the buses, and the average of OPQI of all buses is defined as the OPQI of the network. After the overall PQ performance of different buses and of average are derived, considering both OPQI and the cost, optimized compensation plot can be derived by creating the upper and lower bounds of the cost curve clusters and OPQI curve clusters, four lines in total. The closed quadrilateral area formed by the four lines are the area from which the solutions are selected for optimized PQ compensation. The methodology is implemented on a 124-bus network built from a real power network in Northwest China, with the optimized number of buses to be compensated ranging from 58 to 77.

In the future work, the coherence between different power quality indices will be considered, and the way of weighting factor determination for different indices based on bus sensitivity and actual operation scenario will be investigated to improve the methodology developed at this stage.

REFERENCES