Electric Power Systems Research 160 (2018) 71–88

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

# Dynamic modeling, control design and stability analysis of railway active power quality conditioner

Hossein Mahdinia Roudsari [a], Sadegh Jamali [a,b], Alireza Jalilian [a,b,*]

[a] School of Electrical Engineering, Iran University of Science and Technology, Tehran 16846-13114, Iran
[b] Center of Excellence for Power System Automation and Operation, Iran University of Science and Technology, Tehran 16846-13114, Iran

ARTICLE INFO

*Article history:*
Received 11 June 2017
Received in revised form 3 January 2018
Accepted 26 January 2018

*Keywords:*
Active railway power quality compensator (ARPQC)
Electrified railway
Bi-linear model
Generalized averaged model
Linear control system design
Stability analysis

ABSTRACT

Two-phase three-wire converter has been proposed to compensate the power quality issues in AC electrified railway systems. In this paper, a step-by-step modeling procedure is presented and applied to the compensator to obtain a linear model. The model is then used in a linear control system design and stability analysis of the compensator. The first step is to obtain the bi-linear form of the exact (switched) model of the compensator representing the high and low frequency behavior of the converter. Then, the generalized state space averaging is applied to the bi-linear model to obtain the continuous time model of the compensator. The linear small signal model is derived by differentiating the averaged model around its equilibrium point. Linear control system design is established based on the linear small-signal model to improve DC-link voltage performance. The simulated model of compensator is verified by quantitatively comparing to the previously reported experimental results. The verified simulation model is used to validate the obtained models. Finally, the open loop stability analysis is performed by studying the locus of system eigenvalues with respect to the circuit parameters variations.



## 1. Introduction

There are a fast growing number of electrified intercity railways featuring higher energy efficiency, low air pollution, higher speed, etc. [1]. The supply voltage of electric trains can be DC (600/750/1500/3000$^{V}$) or AC (“11/15$^{kV}$ 16.67 Hz” or “25$^{kV}$, 50/60 Hz”) [2]. Most recent electrified railways use autotransformers to provide 25-0-25 kV traction power supply for the operation of the modern 25 kV electric rolling stock. Independent from being supplied by DC or AC, electrified railway systems impose power quality (PQ) problems such as negative sequence current (NSC), harmonics [3,4], low power factor, etc. to the supply grid [5]. The PQ problems may cause maloperation of the protection relays, vibration, over-heating, etc. in the grid [6,7]. Conventional passive methods such as balanced transformers, using three-phase locomotives, passive filters, phase shifting, etc. used to mitigate the PQ problems [8,9]. Furthermore, various active methods have been recently presented to mitigate the PQ problems; such as: static VAR compensators [9], static compensator (STATCOM) [10], railway power conditioner (RPC) [10], two-phase three wire compensators (TPTWC) [11], hybrid power quality conditioner (HPQC) [12], magnetic hybrid power quality compensator [1,13], etc. An extensive review of the passive and active PQ compensating approaches is also presented in [14].

The satisfactory behavior of the compensators relies on the appropriate selection of components and proper control design. Appropriate modeling is the first step in proper circuit and control design. The majority of the presented works in the literature used trial and error to design the controllers parameters. A few analytical procedures for dynamic modeling and control design of the ARPQCs are presented in the literature. In [15] a modeling procedure is presented for implementation of the nonlinear passive-based control in the current control stage of the converter. Hu et al. also proposed a harmonic model for HPQC, in order to investigate the frequency characteristics of the compensator [15]. The modeling procedure is implemented in the frequency domain and cannot be used in the control design. The majority of works have used PI controller to stabilize the DC-link voltage of the ARPQCs [16]. Regardless of the selected control approach, modeling is the first and key step in control design of the ARPQCs.

* Corresponding author.
*E-mail address:* jalilian@iust.ac.ir (A. Jalilian).

https://doi.org/10.1016/j.epsr.2018.01.027
0378-7796/

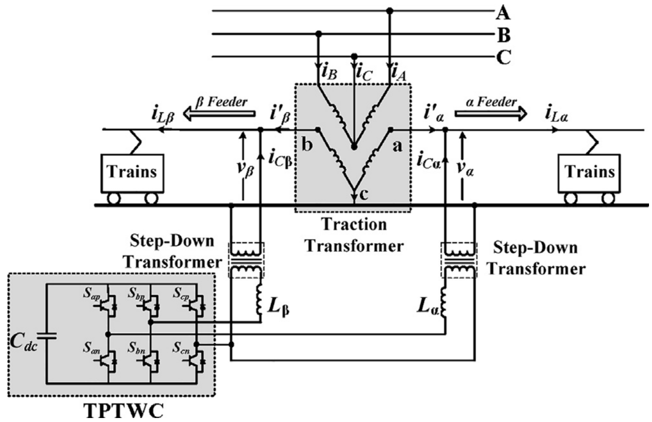


**Fig. 1.** Traction supply system with V/v transformer and TPTWC.

The first step in the modeling of a power electronic converter is to obtain its exact (switched) model or its bi-linear model (BML); which is required for attaining other types of models. The BLM models the high-frequency behavior of the converter as well as its low-frequency characteristics [17]. The BLM is particularly suitable for designing nonlinear control laws, such as variable-structure, Lyapunov approach, matrix inequalities, etc. In general, the models used for control design and stability analysis are simpler than those used for circuit design or simulation. Generalized state space averaged model (briefly generalized averaged model (GAM)) which is also known as dynamic phasor model is widely used in the modeling of power electronic converters including HVDC system [17], doubly fed induction generators [18], quadratic boost converter [19], single-phase full-bridge inverter [20], induction generator excited by a 3-phase inverter [21], bidirectional solid-state transformer [22], matrix-reactance frequency converter [23], etc. This is because of its appropriate dynamic behavior and considerable reduction of processing requirements and simulation time [23,24]. The small signal model of the power electronic converter is obtained by linearizing the large-signal GAM around an equilibrium point. The obtained model can be used in linear control system design [17]. On the other hand, it is required to be ensured that the converter remains stable under variations in operating conditions [17]; hence, stability analysis of the power electronic converters is necessary.

This paper presents a road map for dynamic modeling, control design and stability analysis of the ARPQCs used in 25 kV, 50 Hz electrified railway system. The TPTWC which is proposed by Chuanping et al. [11] is selected as a case study; but, the modeling procedure can also be applied to other compensators with linear current control system. The main contributions of this paper are summarized as:

- The exact BLM of TPTWC as PQ conditioner in electrified railway systems is formulated.
- In the premise of linear control system design, the GAM as the continuous time-invariant model of the TPTWC is obtained which considers only its low frequency (averaged) characteristics.
- By differentiating the GAM, small-signal averaged model of the TPTWC is achieved.
- Linear control system design for DC-link PI controller is established which significantly improves the performance of the TPTWC.
- The stability analysis of TPTWC is performed by studying the locus of system eigenvalues.

The rest of the paper is organized as follows: The TPTWC is introduced in Section 2. Section 3 presents the modeling methodology. The large and small signal models of the TPTWC are established in Section 4. Section 5 is devoted to the linear control system design based on the obtained linear small-signal model. The models are validated in Section 6, and Section 7 is dedicated to the open loop stability analysis of the TPTWC. Finally, Section 8 gives the conclusion and the summary of the findings of this paper.

## 2. Railway electrification system and active power quality compensator

The TPTWC is installed in parallel with Vv traction transformer (Fig. 1) and compensates NSC using the hybrid current control comprised of hysteresis current control (HCC) and dividing frequency control (DFC). Four-quadrant converters are used in the latest generation of electric locomotives to minimize the PQ problem. The locomotives with these converters exhibit unit power factor and minimum interference to the power supply grid. The measurements revealed that the reduction of low-order harmonics increases the emission at high frequencies (2–150 kHz), the so-called supraharmonics [25]. The supraharmonics components are not considered in this paper. Therefore, traction loads are assumed to be pure resistive and inject no harmonic into the system [11]. Loads of $\alpha$ and $\beta$ feeders are:

$$\begin{cases} i_{L\alpha}(t) = I_{L\alpha} \cdot \sin(\omega t - 30^\circ) \\ i_{L\beta}(t) = I_{L\beta} \cdot \sin(\omega t - 90^\circ) \end{cases} \tag{1}$$

To mitigate NSC in the grid side of traction transformers, secondary currents ($i'_\alpha$, $i'_\beta$, and $i'_c = -(i'_\alpha + i'_\beta)$) must be balanced three phases. Therefore, the injected currents by TPTWC not only must balance the consumed power of the feeders, but also shift their phases in a way that their phase difference to be 120°. The mean active current component is defined as $I_{mp} = 0.5(I_{L\alpha} + I_{L\beta})$ and the reactive current