Electric Power Systems Research 80 (2010) 204–214

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Simplified models of a single-phase power electronic inverter for railway power system stability analysis—Development and evaluation

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ARTICLE INFO

Article history:
Received 2 May 2008
Received in revised form
11 September 2008
Accepted 1 September 2009
Available online 12 October 2009

Keywords:
Railway power system
Stability studies
Power electronics
Single-phase
Controller dynamics
Eigenvalue analysis

ABSTRACT

Use of power electronic equipment has increased and introduced new dynamical phenomena in power systems. For example, new electric rail vehicles (locomotives) equipped with modern power electronic traction chains have caused situations of low frequency power oscillations and instability in single-phase railway power supply systems. This paper presents the development and implementation of an instantaneous value model and simplified fundamental frequency (RMS) models of such an advanced electric rail vehicle in order to investigate their representation of low-frequency dynamics. The dynamical behaviour is studied by use of both time-domain simulations and linear analysis (eigenvalues) and the degree of simplifications regarding controller dynamics and power system dynamics are presented and discussed. An enhanced RMS model is tested in order to account for the impact of fast current dynamics on the low-frequency behaviour. The results show that this enhanced model is corresponding more closely to the instantaneous value model than what can be obtained by the traditional RMS simplifications and indicate that current dynamics should be included in stability studies involving power electronic inverters.

1. Introduction

Use of power electronic components in various power systems has expanded during recent years [1]. This is especially seen in power systems where electric motor drives are the dominating loads or renewable energy sources are present [2]. The use of power electronic converters with modern digital control techniques opens a new world of possibilities.

This is also the case in railway power supply where there is demand for fast control of electric motors by light-weight and small-size equipment in order to increase the running performance of electric trains. Almost all new electric (locomotives) today are equipped with three-phase asynchronous motors [3]. In a single-phase AC traction power system, the vehicle interface to the rest of the power supply is a power electronic converter behind an impedance as shown by the line inverter and main transformer in Fig. 1. These new technologies raise new questions about electrical system compatibility [4].

One particular issue that has been focused in the electrical railway community during recent years is power oscillations at low frequency, typically in the range of 0.1–0.3 times the fundamental frequency, that lead to power system instability due to lack of damping. The power electronic based locomotives may interact unfavourable with each other [5] or with the power system components, such as rotating synchronous–synchronous frequency converters [6], making the power system unstable.

In a traditional three-phase power systems with mainly electric machines and passive loads, it can be argued that low-frequency stability studies by time-domain simulations and linear analysis can be performed in fundamental frequency RMS (root-mean-square) mode instead of by time-domain simulations with instantaneous values of voltage and current values [7]. In a power system with dominating non-linear components, and in single-phase system particularly, these traditional tools may not be fully valid any more [8].

It would be of great interest and benefit if already established and classical methods for power system stability studies can be used in systems with power electronic components as well. Hence, the aim of this paper is to investigate to what extent traditional power system modelling of a power electronic inverter reflects low-frequency phenomena in a single-phase system.

This paper presents and evaluates models of the grid interface for an advanced electric rail vehicle (inverter vehicle) as shown in Fig. 1. The models are developed and implemented in a traditional power system simulator, Simpow [9], in both single-phase instantaneous value mode and fundamental frequency (RMS) mode. After an introduction to the fundamentals for single-phase instantaneous values and RMS modes in Section 2, the vehicle and its model are

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doi:10.1016/j.epsr.2009.09.003

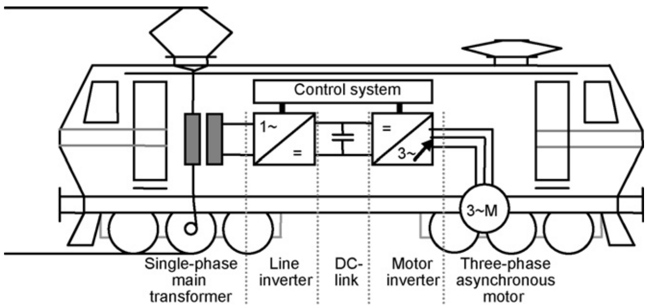

Fig. 1. Sketch of an advanced electric rail vehicle.

explained in Section 3. The different steps of modelling the vehicle, with synchronization controller, active power controller and current controller, are presented in Sections 4–6, respectively, before their stability limits are compared in Section 7. The investigated system is the locomotive model connected to a stiff voltage source through an overhead (contact) line.

2. Single-phase instantaneous value and RMS modes and power

2.1. Instantaneous value and RMS modes

The instantaneous voltages and currents in an AC system in instantaneous value mode can, if harmonics are neglected and the system is in steady state, be described as sinusoidal waves as functions of time t, as in equations (1) and (2). The fundamental angular speed is $\omega_1 = 2\pi f_1$ where the fundamental frequency is given as $f_1 = 16 \times 2/3$ Hz in the traction power system considered. In equation (1) A_u and B_u and in equation (2) A_i and B_i together describe the individual amplitude and phase of the phase voltage u and current i, respectively:

$$u(t) = A_u \cos(\omega_1 t) + B_u \sin(\omega_1 t) \tag{1}$$

$$i(t) = A_i \cos(\omega_1 t) + B_i \sin(\omega_1 t) \tag{2}$$

These instantaneous signals, with fundamental frequency only, can be written in complex form (rectangular or exponential form) as rotating phasors as shown in equations (3) and (4) where θ_{u0} and θ_{i0} are initial displacement angles for the voltage and current, respectively. It is common, however, to choose a reference, θ_u and θ_i, for instantaneous values such that the imaginary parts disappear. $\hat{U}$ and $\hat{I}$ express the peak values of the voltage and current, respectively:

$$\begin{aligned} u(t) &= A_u \cos(\omega_1 t + \theta_{u0}) + jB_u \sin(\omega_1 t + \theta_{u0}) \\ &= \hat{U} \cos(\omega_1 t + \theta_u) = \sqrt{{A_u}^2 + {B_u}^2} e^{j(\omega_1 t + \theta_{u0})} = \hat{U} e^{j(\omega_1 t + \theta_u)} \end{aligned} \tag{3}$$

$$\begin{aligned} i(t) &= A_i \cos(\omega_1 t + \theta_{i0}) + jB_i \sin(\omega_1 t + \theta_{i0}) \\ &= \hat{I} \cos(\omega_1 t + \theta_i) = \sqrt{{A_i}^2 + {B_i}^2} e^{j(\omega_1 t + \theta_{i0})} = \hat{I} e^{j(\omega_1 t + \theta_i)} \end{aligned} \tag{4}$$

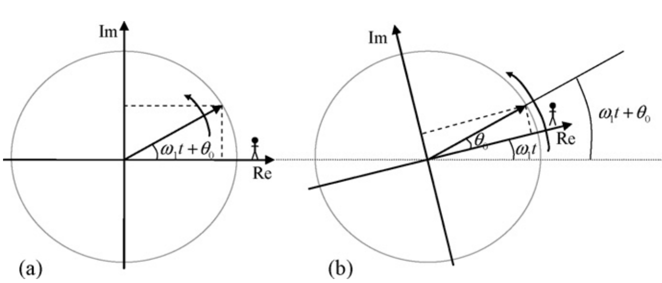

Fig. 2. Stationary reference frame (a) and rotating reference frame (b).

From a sideline perspective as in Fig. 2a), the phasors in equations (3) and (4) are seen rotating with the angular speed ω_1 in the complex plane. Seen in this stationary reference frame, the direction of these phasors is then time-variant, i.e. depending on the instant it is considered—even in steady state.

In order to simplify hand calculations and increase simulation speed for power system analysis it is normal to make use of RMS values and a reference frame rotating at synchronous speed ω_1 as seen in Fig. 2b. Then the arguments of the phasors only describe their mutual displacement from the reference and all steady-state fundamental AC values can be expressed by DC values. The signals are now time-invariant in steady state.

Using RMS values also implies neglecting fast current transients in synchronous machine stators and corresponding series network components [7]. The influence of the changed network frequency in reactance values is also neglected. Using this simplification, the corresponding voltages and currents are as formulated in equations (5) and (6) where there is no time dependency.

$$\begin{aligned} \vec{U} &= \frac{1}{\sqrt{2}}(A_u \cos(\theta_{u0}) + jB_u \sin(\theta_{u0})) \\ &= U_{Re} + jU_{Im} = Ue^{j(\theta_{u0})} = \frac{\hat{U}}{\sqrt{2}} e^{j(\theta_{u0})} \end{aligned} \tag{5}$$

$$\vec{I} = \frac{1}{\sqrt{2}}(A_i \cos(\theta_{i0}) + jB_i \sin(\theta_{i0})) = I_{Re} + jI_{Im} = Ie^{j(\theta_{i0})} = \frac{\hat{I}}{\sqrt{2}} e^{j(\theta_{i0})} \tag{6}$$

The equations have become time-invariant as the $\omega_1 t$ term in the angle is omitted. The synchronously rotating phasor coordinate system can be considered as a global synchronously rotating dq system, where the direct (d) axis is aligned with the real axis and the quadrature (q) axis is aligned with the imaginary axis.

The voltage drop $\Delta u(t)$ or $\Delta\vec{U}$ over a resistor R and an inductor L can be described as in equation (7) for instantaneous values and (8) for RMS values, respectively. The term $\omega_1 L$, called the reactance X, leads to the rotationally induced voltage drop given by the fundamental current alternation. In the model of series inductors implemented in this paper, such as power lines and transformers, the fundamental frequency is assumed to be constant, i.e. $\omega_1 = 1$ pu. Note that RMS current in equation (8) is no longer a state variable, i.e. it is allowed to change with infinite time-derivative:

$$\Delta u(t) = R\, i(t) + L\frac{di(t)}{dt} \tag{7}$$

$$\begin{bmatrix} \Delta U_{Re} \\ \Delta U_{Im} \end{bmatrix} = \begin{bmatrix} R & -\omega_1 L \\ \omega_1 L & R \end{bmatrix} \begin{bmatrix} I_{Re} \\ I_{Im} \end{bmatrix} = \begin{bmatrix} R & -X \\ X & R \end{bmatrix} \begin{bmatrix} I_{Re} \\ I_{Im} \end{bmatrix} \tag{8}$$

For the study of power electronic components, a local synchronously rotating dq reference frame, such as commonly used when modelling synchronous machines, is often established [10]. However, an important difference from classical power system modelling is that the current is kept as a state variable including the fast line current dynamics given by the term $L{\cdot}di/dt$ as seen in Ref. [10]. The voltage drop over the inductive reactance then becomes as in equation (9) when considered in the real and imaginary axis coordinate system already introduced. In this paper this introduction of current as a state variable is called the 'enhanced' RMS mode or 'RMS $L{\cdot}di/dt$' (in contrast to 'normal' RMS mode).

$$\begin{aligned} \begin{bmatrix} \Delta U_{Re} \\ \Delta U_{Im} \end{bmatrix} &= \begin{bmatrix} R + L\frac{d}{dt} & -\omega_1 L \\ \omega_1 L & R + L\frac{d}{dt} \end{bmatrix} \begin{bmatrix} I_{Re} \\ I_{Im} \end{bmatrix} \\ &= \begin{bmatrix} R + L\frac{d}{dt} & -X \\ X & R + L\frac{d}{dt} \end{bmatrix} \begin{bmatrix} I_{Re} \\ I_{Im} \end{bmatrix} \end{aligned} \tag{9}$$