Design of Proportional-Resonant Control for Current Harmonic Compliance in Electric Railway Power Systems

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***Abstract*—This paper presents the process of designing proportional-resonant controller for a four-quadrant rectifier in electric railway traction system. In the context of ever-stricter power quality and electromagnetic compatibility standards in electric railway power systems, developers of electric locomotives need to adapt with new ways to comply. This paper develops on the process of designing a four-quadrant rectifier proportional-resonant control for mitigation of low frequency current harmonic distortion, a novel method in the field of railway EMC. The control parameters are determined through analytical modeling of the rectifier through transfer functions. For the purpose of studying the harmonic distortion mitigation effects, only the current control loop was modeled and designed. The modeling starts with simplification of the model via large-signal modeling of the power converter. The parameters of the circuit then were used to develop the transfer functions, and select the appropriate parameter values of the current loop plant. The control loop and parameters were evaluated on test locomotive to validate the control, with results confirming the improved impact on the electromagnetic compatibility and conformity to regulation.**

Keywords—electric railway traction system, four-quadrant rectifier, proportional-resonant control, harmonics, ;large signal model.

I. Introduction

Electric railway traction systems (ERTS) are an important part of human transportation, especially in European and East-Asian countries. An increasing number of high-power converters on rolling stock (RS) for traction or auxiliary function, create an electromagnetic combability (EMC) problem with the railway power system [1-3]. Another issue of EMC in ERTS is heavy wireless communication systems integration, which creates problems of compatibility between switching devices and conducted and consumer or railway communication systems [4, 5]. These effects are drastic and hazardous to the safety of passengers, vehicles and can impact the efficiency of switching in the power converters [6].

To mitigate the EMC issues between rolling stock and electric railway power system there are a series of standards that are put in place. In the European space, the framework for the EMC between the RS and the infrastructure systems on electrified railways is defined by such standards as the European EN 50 121, EN 50 163, EN 50 238, EN 50 388. Even though these standards were developed for international use, national rail administrations define their own application of the standards, due to historical reasons in the development of the electric railway systems. An example is Norway's and Sweden's ERTS. These two countries implemented their own regulatory standards based on the European ones, such as the NIM NES 2009-07-1, which provides technical specification for EMC of rolling stock, power systems and other vehicles connected to the same supply system.

Currently, in ERTS solving the EMC problem in is by implanting active and passive filtering on all stages of power conversion. Other methods do not require such heavy investments in design and manufacturing and can be easier implemented. Such methods are applying control methods for the switching devices or different modulation techniques for driving power switches.

For ERTS, the two power converters on the RS that have the possibility for control method improvement are the power rectifier, auxiliary converter, or the traction inverter. This study proposes the use a novel control method for ERTS rectifiers, the Proportionally Resonant (PR) control [7, 8]. PR

Horizon 2020 research and innovation programme Marie Sklodowska-Curie: grant agreement No. 812753 – ETOPIA project.

control is a predictive control method that allows to have a high gain on the resonant frequency, with the cost of dependency on the accuracy of system model and reference current prediction [9]. This method was previously successfully implemented in photovoltaic plants to minimize the distortions in the grid by the inverters [10], to generate harmonic command reference for active power filters, especially for single-phase systems [11], however in ERTS it lacks implementation. The method was considered before in research for traction, but with small electric vehicles, and completely different structure of traction [12, 13]. The specific of low allowed frequency of IGBT switching is not considered in the developed test presented in [12,13], thus requiring an expansion in the direction of high-power converters for ERTS.

In ERTS, the PR control method would allow the rolling stock to filter the incoming distortions from the grid and to not allow the traction drive to pollute the power supply grid, especially in the regenerative braking of the rolling stock. The big advantage of a controlled rectifier is the possibility for the traction drive to act as generator, thus the conducted emission from the traction drive must also be mitigated for the electric traction drive to abide the regulations, a field of research unexplored yet.

In this paper is presented the design procedure of control parameters of the 4-quadrant controlled rectifier with main functions to provide stable output voltage and to mitigate current conducted emissions in low frequency range for railway traction applications. The paper starts with a model design, where the necessary transformations are made to be able to model the switching power converter. Then the mathematical model of the current loop is described in transfer function form, and the parameters of control are selected. Lastly the control parameters are validated on a test locomotive and the resulted harmonics are compared to regulated values.

II. Model Design

The ERTS is a complex system, with model components starting from the contact line, pantograph, power transformer and to the power converters and electric motors. The complete ERTS model diagram is presented in Fig. 1.

The purpose of this paper is the optimized PR control of the rectifier to eliminate a set of determined harmonic order currents, thus the model will be limited to the four-Quadrant Rectifier (4QR) with a simulated load. The analyzed topology of the rectifier is limited for the purpose of this paper from the main transformer output, where the output voltage is v_s, and the output of the rectifier which is a DC circuit and the load is represented by the resistance *R*, as shown in Fig. 2. The simplification of the load to a resistance is done to represent a perfect DC load, which represents the behavioural parameters of the system satisfactory to the purpose of this preliminary design.

The design process of a control systems starts with identifying the objectives of the control. The objectives in the control of the rectifier in this system are:

1. Regulate output voltage V_0 as the reference V_0* [11]
2. Keep unitary power factor, i.e., the grid side current should have the same phase as the grid voltage
3. Grid side current *is* and output voltage V_0 should reject the harmonics caused by the grid voltage

The design process then continues with identifying the mathematical model to be controlled. The model is identified from the electric circuit of the model presented in Fig. 2. The parameters in the mathematical model of the 4QR (Fig. 2) are:

- Grid voltage v_s,
- $v_s(t) = E sin(\omega_0 t) + \sum_k E_k sin(k\omega_0 t + \psi_k)$ (1)

  where k=3,5,7 and 9, $\omega_0 = 2\pi f_0$
- Grid current $i_s(t)$
- Secondary inductance of the transformer *L*
- Parasitic resistance of the secondary inductor and resistance of power switch *r*
- Output DC link capacitor: *C*
- Input impedance of the traction inverter at DC side: *Z* [simplified case as *R, to represent the resistive load in steady state on the DC-bus*]
- Voltage between point *a* and *b*, $v_{ab}(t)$
- Currents at load side: $i_L(t)$, $i_c(t)$ and $i_0(t)$
- Unipolar PWM signal $u(t)$ is:

$$u(t) = S1 - S3 \quad (2)$$

where *S1, S2, S3, S4* – signals on Q1, Q2, Q3, Q4; *S2* = inverse of *S1*, *S4* = inverse of *S3; u(t)*□(-1,0,1).

To analyze the behavior of a switching power converter it is necessary to simplify the model to linear components. In this methodology large signal switched model is used, and its' mathematical model is described by eqs. (3), (4). It can be regarded as two subsystems related by the switching function, with equivalent circuit of controlled voltage/current source (Fig.3).

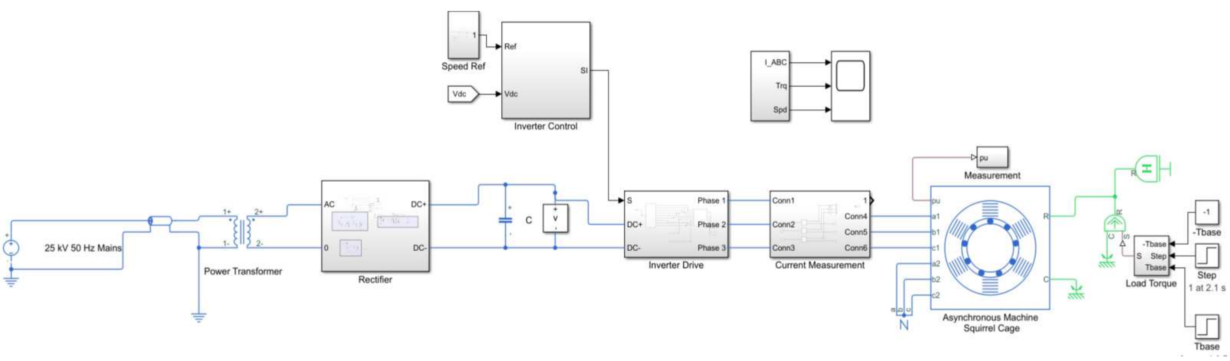


Fig. 1. Electric Railway Traction System Model

$$L\frac{di_s(t)}{dt} = v_s(t) - u(t)v_0(t) - i_s(t)r \quad (3)$$

$$C\frac{dv_0(t)}{dt} = u(t)i_s(t) - i_0(t) = u(t)i_s(t) - \frac{v_0(t)}{R} \quad (4)$$

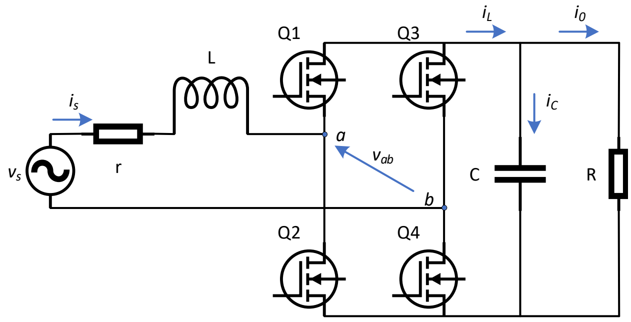
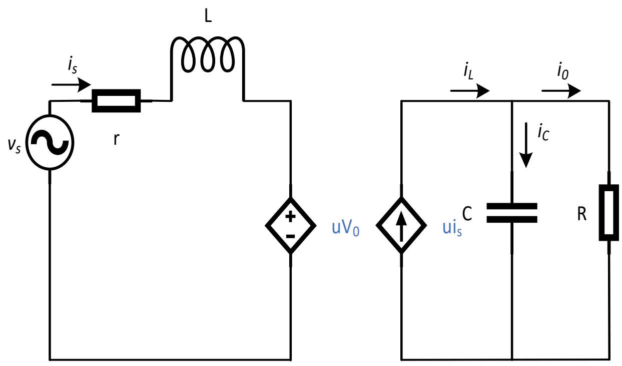


Fig. 2. 4-Quadrant bi-directional rectifier topology and values of



The mathematical model (Fig.3) can be divided in two plants which are considered decoupled. Equation (3) describes the inner AC plant model, and from (4) the outer DC plant model can be determined. For the purpose of this paper, only the current loop will be modeled, and the parameters will be determined. The modeling starts with the averaging operation of (3) for a single switching period T. Leading to:

$$< L\frac{di_s(t)}{dt} >_0 (T) = \\ = < v_s(t) >_0 (T) \\ - < u(t)v_0(t) >_0 (T) \\ - r < i_s(t) >_0 (T) \quad (5)$$

For the inner AC plant, the following simplifications are considered:

- $< L\frac{di_s(t)}{dt} >_0 (t) = L\frac{d<i_s(t)>_0(t)}{dt}$ (7)
- The higher order harmonic coupling between u and v_0 is neglected for this purpose, and it can be assumed that:

$$< u(t)v_0(t) >_0 (t) \approx < u(t) >_0 (t) < v_0(t) >_0 (t) \quad (8)$$

- Notation:

$$< u(t) >_0 = \beta(t) \quad (9)$$

- Voltage loop and current loop are decoupled, and the current loop is much faster than the voltage loop, then it can be assumed that the output voltage v_0 variation is small, and it can be set as the reference voltage

$$< v_0(t) >_0 = V_0^* \quad (10)$$

Combining the voltage equation (1) with the equations determining the large switched signal model and the simplification considered (3-10), and applying the Laplace transform to study the frequency behavior of the system, we reach the following equation from which the transfer function will be determined.

$$i_s(s) = \\ = -\frac{V_0^*}{Ls+r}\beta(s) + \frac{E\omega_0}{(Ls+r)(s^2+\omega_0^2)} \\ + \sum_{k=3,5,7,9} \frac{E_k\{\sin(\psi_k)\, s + k\omega_0 \cos(\psi_k)\}}{(Ls+r)(s^2+(k\omega_0)^2)} \quad (11)$$

In the above equation, the first term is used for control, other two terms are noise due to the harmonics of the grid voltage. The second term is the second order harmonic compensated by a passive filter indiscriminately for such topology of rectifier, on the DC bus. The higher order harmonics are compensated in the current control loop design stage.

Based on the considerations from the above, the current plant transfer function for current is determined as the report of the output of the current equation and the input of the system, which is the switching equation in frequency domain:

$$H_i(s) = \frac{i_s(s)}{\beta(s)} = -\frac{V_0^*}{Ls+r} = -\frac{V_0^*/r}{\frac{L}{r}s+1} \quad (12)$$

III. Current Control Loop Design

After the current plant transfer function has been identified, the current control loop design must be designed. The control diagram of the rectifier in Fig.2 is shown in Fig. 4. The current loop has the PR current controller block that is the purpose of this paper, to limit the harmonics on the supply side, will be developed on in this chapter.

An ERTS uses the voltage from a secondary of a transformer, we consider the supply voltage of E=1300 V, frequency f_0=50 Hz, secondary winding on the transformer inductance L=1 mH, secondary winding on the transformer resistance r=3 mΩ, and the DC reference voltage V_0*=1800 V, DC link capacitor C=12 mF, and a DC load of R=3 Ω. For these values, the plant function is calculated in (17), and the plant transfer function graph is shown in Fig. 4.

$$H_i(s) = \frac{-600000}{0.3333s+1} \quad (13)$$

The cut-off frequency of the current loop gain, without control, is 286.5 kHz, as shown in Fig. 5

The current PR controller is designed via the loop-shaping method. The general equation of the PR controller[4] is presented below:

$$H_{PR}(s) = K_{pc} + \frac{2K_{ic}s}{s^2+\omega_0^2} \quad (14)$$

The task of designing the controller then has reached the point of determining the two control parameters K_{pC} and K_{ic} .

The K_{iC} affects only locally at the fundamental frequency f_0 and does not affect much the cut-of frequency of the loop gain, which can be assumed to be the same regardless of the second term in the PR control equation. To simplify the calculations, K_{iC} was selected to be 0, thus reaching the simplified loop gain:

$$T_{OL}^{s}(s) = H_{PR}(s)H_i(s) = K_{pC}\left(-\frac{\frac{V_0^*}{r}}{\frac{L}{r}s+1}\right) = -\frac{\frac{V_0^* K_{pC}}{r}}{\frac{L}{r}s+1} \quad (15)$$

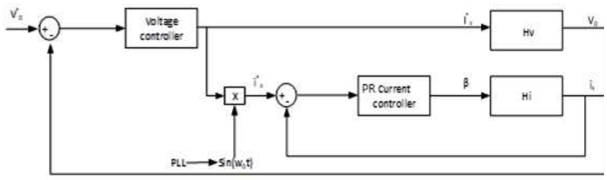


Fig. 6. Control diagram of the rectifier

As it can be noticed in (15), the current control loop does not depend on the DC circuit parameters, meaning it's independent of the DC load.

To compute the K_{pC}, we select the cutoff frequency f_c = 300 kHz, and compute K_{pC} by setting the amplitude of the loop gain as 0 dB.

To compute K_{ic}, it is necessary to impose a suitable phase margin for the loop gain. Since the phase margin for the original loop gain (H_i), and the loop gain with K_{pC} are already reach 90 degrees, for the final loop gain with K_{pC} and K_ic, the set phase margin is 90 degrees. The plot of K_{iC} and K_{pC} against cut-off frequency (Fig. 6) will allow to determine the optimal control coefficients for the current PR controller. There are two pairs of parameters identified bellow for 300 kHz and for 800 kHz cut-off frequency.

The result of the process control design is presented in Fig. 7. It shows clearly that the cut-off frequency of the loop is 300 kHz, meaning it converges to a stable solution in time. The total phase shift, on the other hand, at frequency lower than 50 Hz reaches -270^0, and after 50 Hz makes a steep jump to the stable 90^0 shift.

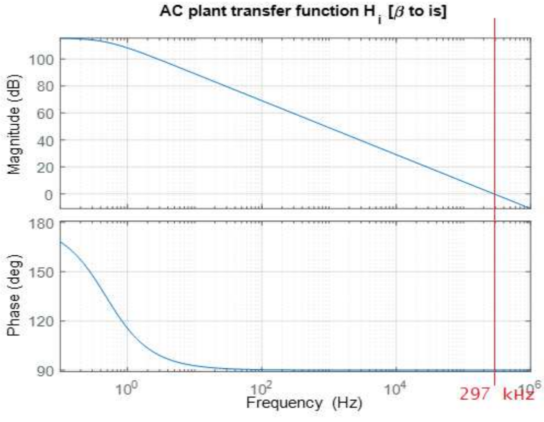


Fig. 7. Gain and phase shift of the current plant

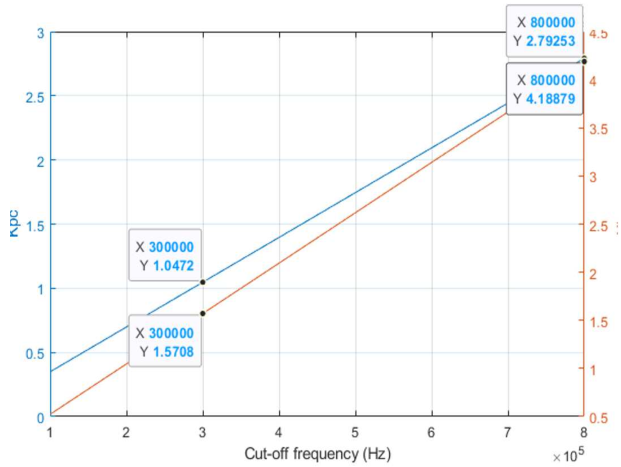


Fig. 4. K_{iC} and K_{pC} as functions of cut-off frequency, at 90 degree fixed phase-margin

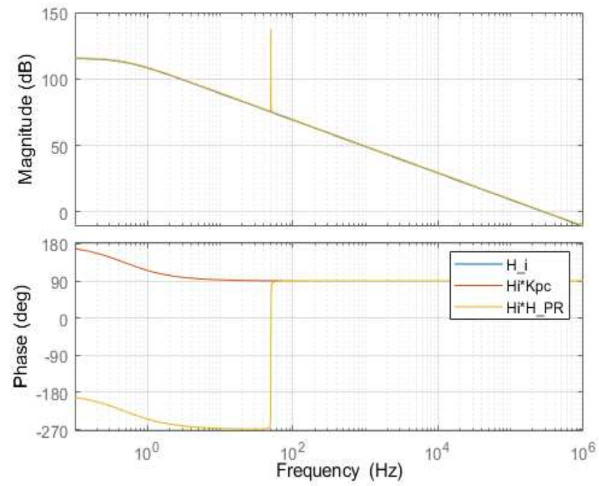


Fig. 5. Gain and phase-shift of the current control loop with H_i K_{iC} K_{pC} H_i*H_{PR}

IV. Validation

The designed control parameters require validation before considering it a successful tune. A most practical approach is to validate on the designed parameters a test locomotive in field conditions. Measurements were done to validate the results with the designed control parameters on a test locomotive (Fig. 8). The first visual observation of the current is the wave shape, which is very close to the sinusoidal, with small periodic distortions, which demonstrates good parameter design.

To determine the harmonic weights of controlled harmonics by the PR control, the current and voltage were decomposed with Fast Fourier Transform (FFT). The current decomposition of FFT presents the values in Table I shows that the values of harmonic weights are bellow regulative thresholds for the 3rd, 5th, 7th, and 9th current harmonics - 5.0%, 3.0%, 3.0%, and 3.0%, respectively, of the rated current of the European standards or national standards, such as the ES 2009-07-01, this validating the determined control parameters.

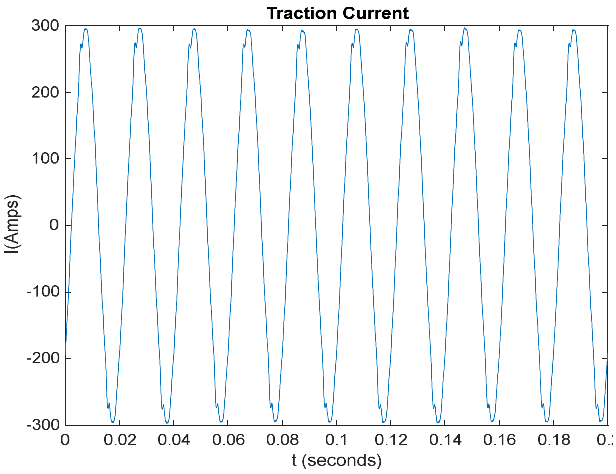


Fig. 8 Traction parameters of supply current of locomotive with PR-controlled 4-QR

TABLE I. HARMONIC WEIGHTS OF SUPPLY CURRENT

Frequency, Hz	Harmonic order	Current harmonic, A	Current harmonic weight, %
50	1	294.15	100
150	3	2.9	0.9846
250	5	1.28	0.4357
350	7	5.56	1.8904

Currently the locomotives equipped with 4QR are controlled by symmetrical 3-level PWM techniques [2]. The functioning of current topology was presented previously in [2], with the corresponding issues in creating resonant overvoltage on certain harmonic levels. The same type of locomotive, with exactly the same hardware, but with the aforementioned designed PR-controller presented the results in Fig. 8 and TABLE I. The designed control tested with a real locomotive show advantages of reduced harmonic distortion on the specified harmonic orders, and possibility of eliminating the identified harmonics in [2], with addition of current harmonic orders in the process of designing the current control loop.

V. CONCLUSIONS

Regulatory environment on European and national levels in ERTS aims to improve the electromagnetic coexistence and reliability of the rolling stock and the entire system. Of the different solutions to improve the current distortions, implementing specific control methods may be a cost-effective solution.

This paper presents the process of designing a proportional-resonant controller for a four-quadrant rectifier on the traction system of the locomotive to improve the compatibility of newly designed locomotives with the developing regulations, such as the EN 50388 and NES 2009-07-01.

The method to allow for the simplification of modeling was the large signal switched method, and the calculated control parameters showed valid results on test locomotives. This validated method for the traction stage of the locomotive showed positive results, which can be developed for regenerative braking and stability analysis. A complex design study for different functioning stages of the locomotive and stability analysis are next required steps to an industrially applicable improvement design methodology.

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