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An intelligent control method for capacity reduction of power flow controller in electrical railway grids

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ABSTRACT

Adoption of smart grids has led to significant opportunities in the optimal operation of systems and energy consumption in utility grid loads. Among the various grid loads, electrical railway networks (ERNs) are known as one of the most important and critical end users due to their high power consumption. Energy management and power quality domination in such a network are already concerns of researchers. The railway power flow controller (RPFC) is a commonly used system to manage the optimal energy consumption and power quality problems of ERNs. This paper presents a comprehensive study of an RPFC power rating and a new compensation strategy with the objective of reducing the installed capacity in several consecutive traction power substations (TPSs). This technique is implemented through the use of a Yd transformer with multiple phase connections and the central Steinmetz-based intelligent control system (SICS). Through coordination with the internal control systems, the optimal mode of the active and reactive powers transferring in different phases is calculated by the central SICs and applied to each TPS. The proposed control strategy substantially diminishes the RPFC converter's power rating and installation costs. A real-time laboratory platform for the smart-grid based proposed method is provided using Opal-RT emulator to confirm the theoretical analysis with the desired precision representing the real power system behavior.

1. Introduction

The electrical railway network has become one of the most and critical end-user loads of the utility grid. The energy management and power quality issues in such a network are major concerns all over the world. These networks impose several critical power quality problems to the utility grid [1–4]. The considerable quantity of the negative-sequence current (NSC), lower power factor (PF), voltage imbalance, and high harmonic content are substantial problems [5–8]. Over the years, various methods have been proposed to deal with these problems, but because of important restrictions, they could not be as effective [9–11]. After reports of satisfactory field testing results, railway power quality compensators became popular for railway networks [12,13]. Thereafter, numerous researchers investigated various aspects of RPFC, including configurations, compensation strategies, and control systems [14–17]. Despite that the capacity of RPFC is highly momentous, it has not been investigated completely in previous studies. It is noteworthy that the approximate cost of power converters is USD 60 per kVA and the rating of the installed RPFC in every TPS can be greater than 10 MVA [18,19]. Therefore, the high cost of RPFC systems is the main barrier to their implementation and promotion in AC and high-speed railway systems. Recently, a hybrid device composed of active and passive compensators, called the hybrid power quality compensator (HPQC) was presented in order to reduce the operation and DC-link voltage levels and the rating of the compensator [19,20]. This method is based on partial compensation and has weaknesses in compensating. Ma et al. proposed a simplified half-bridge based converter that decreased the number of power switches in RPFC [21]. Nevertheless, reducing the number of switches in the RPFC converter increases the voltage and current stress over the switches. Furthermore, this topology consists of two DC-link capacitors in series, which require a complex and difficult controlling system to stabilize the DC-link voltages. A reduction method using TSC together with RPFC was presented in Ref. [22] to keep the power rating under the optimal value. This strategy has some drawbacks, such as a wide range of harmonics caused by thyristor switching and additional installation costs of TSC. In Ref. [23], a

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Nomenclature

Acronyms

CIR	Current imbalanced ratio
ERN	Electrical railway network
HPQC	Hybrid power quality compensator
IRP	Instantaneous reactive power
ICS	Internal control system
NSC	Negative sequence current
NLPF	Numerical low-pass filter
OCS	Overhead catenary system
PLL	Phase locked loop
PF	Power factor
RPFC	Railway power flow controller
SSN	State-space nodal
SICS	Steinmetz-based intelligent control system
TSC	Thyristor switched capacitor
TPS	Traction power substation

Indexes

Yd	Wye-delta transformer
Ynd	Grounded wye-delta transformer
R,L	Right and left sections of TPS
ζ	Total load imbalance ratio
ζ_r, ζ_l	Load imbalance ratio of left and right section
$\dot{V}_A, \dot{V}_B, \dot{V}_C$	Primary side three-phase voltages of TPS
V_{ph}, V_L	Phase voltage and line voltage
$\dot{V}_R, \dot{V}_{ac}$	Right feeder voltage on secondary side of TPS
$\dot{V}_L, \dot{V}_{bc}$	Left feeder voltage on secondary side of TPS
θ_a	Phase angle of $\dot{V}_A$
a	Conversion ratio of the transformer
V	Effective value of phase voltage
$\dot{I}_a, \dot{I}_b, \dot{I}_c$	Secondary-side currents of TPS transformer
i_R, i_L, i_G	Secondary-side currents of TPS
$\varphi_a\varphi_b$	Load angle in right and left section
i_A, i_B, i_C	Primary side three-phase currents of TPS
i''_R, i''_L, i''_G	Compensating currents
i_{qr}, i_{ql}	Reactive components of i''_R, i''_L, i''_G
i'_R, i'_L, i'_G	Active components of i''_R, i''_L, i''_G
S_T	Apparent power of TPS transformers
P_{LR}, P_{LL}	Active powers of traction loads in right and left sections
V_L	Effective value of voltage
I	Effective value of current
i_{LR}, i_{LL}	Traction load currents in right and left sections
I_S	Effective value of symmetrical and balanced current
I_{ph}	Phase current
i_{rR_1}, i_{rL_1}	Fundamental reference currents of RPFC
i_{LR_1}, i_{LL_1}	Fundamental traction load currents in right and left sections
S_{CR_1}, S_{CL_1}	Fundamental apparent powers of RPFC converters
$\dot{V}_{R_1}, \dot{V}_{L_1}$	Fundamental secondary side voltage of TPS
$i^*_{rR_1}, i^*_{rL_1}$	Conjugate of fundamental reference currents of RPFC
P_{CR}, P_{CL}	Active powers of right and left converter
Q_{CR}, Q_{CL}	Reactive powers of right and left converter
$S_{CR_{\max}}, S_{CL_{\max}}$	Maximum capacity of right and left converter
S_{RPFC}	RPFC power rating
S_{conv}	Converter capacity
$\overline{P}_{ab}, \overline{P}_{bc}, \overline{P}_{ca}$	Active power consumption in each phase
$\overline{P}_{AB}, \overline{P}_{BC}, \overline{P}_{AC}$	Total active power consumption of TPS phases
$\overline{P}_{\min}$	Minimum of active powers $\overline{P}_{AB}, \overline{P}_{BC}, \overline{P}_{AC}$
$\overline{P}'_{AB}, \overline{P}'_{BC}, \overline{P}'_{CA}$	Imbalanced active powers
$\overline{P}_{\max}$	Maximum of active powers $\overline{P}'_{AB}, \overline{P}'_{BC}, \overline{P}'_{CA}$
$\overline{P}''_{AB}, \overline{P}''_{BC}, \overline{P}''_{AC}$	Per-unit values of the imbalanced network
K	Distribution coefficient of active powers
p'_1, p'_2	Amount of active powers extracted by SICS
q'_1, q'_2	Amount of reactive powers extracted by SICS
$S_{conv1}, S_{conv2}, S_{conv3}$	Capacities of each back-to-back converters in three TPSs
$\dot{V}_{Rh}, \dot{V}_{Lh}$	hth-order harmonic voltage of secondary side of TPS
i^*_{rRh}, i^*_{rLh}	Conjugate of hth-order harmonic components of RPFC reference currents
$S_{\max}$	Maximum power rating
THD_i	Total harmonic distortion of currents

combinatorial compensation strategy for the RPFC system is presented. This method is valid in case of six consecutive TPSs with a phase rotation of Yd5 and Yd11 transformers. However, this strategy is rarely implemented because of the six TPSs supplied by the unit upstream grid. In order to decrease the number of TPSs and obtain a practical solution, an intelligent method is presented in Refs. [24] and [25]. Notwithstanding reducing the number of TPSs from six to three, this method is introduced only in the presence of linear loads and all discussed theoretical analyses are based on the fundamental frequency and offline working mode. Nevertheless, the main characteristic of an electrical railway system is harmonic currents absorbed by the train, which makes this method ineffective in the presence of non-linear loads. In this paper, a detailed study on the RPFC power rating under various traction load translocations has been accomplished. A new intelligent smart-grid based control strategy is presented that has not only the specifications of the previous control methods, like simultaneous compensating of NSC, harmonics, and reactive power, but also a considerable capability in the diminution of the RPFC power rating. By controlling the active and reactive power intelligently, the proposed SICS implements the Steinmetz theory over three consecutive TPSs. In other words, by generating lag and lead modes in different sections fed by rotation phases, a virtual Steinmetz circuit is created that leads the network to be symmetrical. The contents of this paper are organized as follows. In Section 2, the configuration and operation principles of RPFC are presented and then mathematical equations and theoretical analysis regarding to RPFC power rating are investigated. In Section 3, the proposed compensation control strategy, including choosing the TPSs configuration, transformers connections, and the combinatorial compensation strategy based on the Steinmetz theory, have been studied in detail and compared with traditional compensation methods. In Section 4, simulation results based on MATLAB are presented and compared with the theoretical results. In Section 5, the FPGA-based RT-LAB real-time platform is executed for the proposed system. Finally, Section 6 concludes this paper.

2. Overview of RPFC principles

2.1. RPFC configuration and analysis of compensation principles for Ynd transformer

The structure of a 1 × 25 kV railway power supply system together with the RPFC is illustrated in Fig. 1. Different transformer connections are used in electrical railway systems as a traction transformer [26]. *Ynd* is one of the widely used transformers in railway systems because of its dominant power-rating utilization and simple and cheap structure compared to other traction transformers [16,26]. Therefore, the Ynd11 transformer has been selected to put the proposed RPFC-based system into operation. In order to calculate the compensation voltages and currents, the load imbalance ratios are expressed as the load current of the section over the full load current of the section [27]. Therefore, ζ_l