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Measurement and modeling of the propagation of the Ripple Control Signal through the distribution network

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ABSTRACT

The paper deals with the estimation of the vertical propagation of the Ripple Control Signal (RCS) through the distribution network segment. Magnitude of the RC signal is determined at various points in the network using in-situ selective pulse measurements as well as simplified model of the distribution network based on the antenna theory. Measurements are carried out in the 3-phase system on 3 voltage levels, 110 kV, 10 kV and 400/230 V, respectively, in either indirect or direct configuration, depending on nominal voltage. Distribution network segment is modeled as an antenna excited with voltage source on one end and terminated with corresponding impedance on the other. The current induced along the distribution cable is determined by solving the corresponding Pocklington integro-differential equation in the frequency domain. The numerical solution is undertaken via Galerkin–Bubnov scheme of the Indirect Boundary Element Method (GB-IBEM). Results obtained via different methods seem to agree satisfactorily.

Introduction

Ripple Control Signal (RCS) represents one-way communication method, where the signal generator is connected to medium voltage (MV) or high voltage (HV) distribution grid, via stepping-up transformer and corresponding filters, enabling signal transmission to a various number of receivers [1]. RCS cannot be described as a continuous wave, but rather as a telegram, since it is based on the Amplitude-Modulated (AM) carrier [2]. The telegram is defined by a protocol and contains a specific command depending on the particular purpose of the signal. RC signal magnitude is about 1–5% of the grid's nominal voltage and it is injected into all 3 phases instantaneously (without phase shift) at frequency in the range of 110–3000 Hz [2,3]. Audio frequency Ripple Control Signal is mainly utilized to control loads in the distribution network. Except for the aforementioned purpose, RCS is used for facilitating the energy tariff policy, network synchronization, control of energy meters and public lighting, switching customers' loads, load shedding, etc., in areas hundreds of kilometers away from central control unit [3]. In the last decade, researchers' attention has been focused on the application of the RC signal for the earth fault location in the MV networks [4]. Ripple control is used in Australia, Austria, Belgium, Bosnia–Herzegovina, Croatia, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Japan, Libya, Luxembourg, Macedonia, Montenegro, the Netherlands, New Zealand, Serbia, Slovakia, Slovenia, South Africa, Sweden, Switzerland and the USA [5,6].

The signal magnitude at the low voltage (LV) level should be at least 0.5% of the nominal voltage when measured on the input terminals of the RCS receiver. However, based on the long-terms measurements and studies arising from it, reliable operation requires magnitudes of 0.9% or better [7,8].

The change of magnitude of the Ripple Control Signal is determined by multiple parameters, e.g. loads connected to the grid, various harmonic filters, reactive power compensation capacitors, generators, grid impedance etc. [9]. Since the economic development of the area covered by the distribution grid is followed by the increase of the connected electrical equipment, the impedance of the grid is altered resulting in the amplification or the attenuation of the RCS, as it will be shown.

In the past decade, the power utility companies and researchers were faced with the particular issues related to the RCS. The Ripple Control Signal may be significantly amplified when injection frequency is close to resonant frequency of the distribution grid, resulting in signal miss-detection and consequent malfunction of the RCS operated loads, i.e. hot-water heaters, public light, etc. [3,9,10]. This phenomenon is also detected in lightly loaded rural distribution lines and in the presence of distributed resources [3,11–13]. On the other hand, problem of the RCS attenuation

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due to poorly tuned harmonic filters has also been found to induce problems [14]. Additionally, it has been reported that RCS has caused difficulties with light bulbs flicker, racing clocks in smart meters and audible noise from ceiling fans [2,9,10].

These phenomena and related difficulties show that the behavior of Ripple Control Signal should be more thoroughly investigated. However, research undertaken in this paper is focused on the RC signal vertical propagation (from high voltage levels to low voltage levels) applying the real-time measurements in conjunction with numerical modeling. The RCS signal injected at 110 kV at frequency of 208.3 Hz with the typical signal duration of 1 min and magnitude of 2% of the nominal voltage level is analyzed. Various segments of the distribution network have been modeled using the antenna theory, where power cables have been represented using thin wire approximation [15–17]. Previously reported models of the Ripple Control Signal propagation are based on a circuit analysis method using passive and concentrated elements, as in PSCAD©/EMTDC™ [9,10] or π-elements grid incorporated in Alternative Transients Program (ATP) [3]. The calculation of the frequency response of the network using node impedance matrix is performed in [1,18]. Taking into account radiation properties of the cables, thus enabling precise calculation of the signal loss is the primary advantage of the full-wave approach used in this paper.

Description of the measuring site and the measurements performed are outlined in 'Site description and measurements'. In 'Antenna model of the distribution network segment', Pocklington integro-differential formulation for the calculation of the current distribution along the power cable, above and below ground, is defined, as well as Galerkin–Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) used for solving the corresponding equation. 'Measurement and numerical results with comparison' gives the results of the performed measurements, as well as the results of numerical modeling with comparison and detailed comments proving applicability of the numerical model. At the end, some concluding remarks are given.

Site description and measurements

Measurements and modeling were executed based on the actual field conditions in one section of the Croatian distribution grid. The most important data regarding field conditions is reported here and more detailed information can be found in [1]. RCS generator is connected on 110 kV voltage level via 29.725 MVA bonding transformer and bonding filter based on the capacitive RAP-scheme, while the signal itself is injected in the form of telegram at frequency 208.3 Hz and level of 2% of the nominal voltage using Ricontic b time raster in conjunction with Versacom protocol. As pointed out in the Introduction, the goal of the measurements was to experimentally verify the accuracy of the antenna theory based model. To obtain universal set of results, the segment of the distribution grid containing 3 voltage levels, 110 kV, 10 kV and 400/230 V, respectively, was selected and the vertical propagation of the RC signal measured. Measurement site scheme is depicted in Fig. 1.

The signal is injected at 110 kV voltage level in the (220)/110/35 kV substation (SS1). The segment of the grid connecting substation SS1 with another 110/10 kV substation (SS2) via multiple single-phase aluminum conductors with the cross-section of 1000 mm^2 and copper screen with the cross-section of 95 mm^2, XLPE inner insulation and outer PVC insulation has been analyzed. 110/10 kV transformer (T1) is characterized by rated power of 40 MV A and short circuit voltage of 14.52%. Transformer T1 is connected to 10/0.4 kV transformer (T2) characterized by rated power of 630 kV A and short circuit voltage of 4.2% via multiple single-phase aluminum conductor with the cross-section of 50 mm^2. Finally, low voltage supply cabling (400/230 V) is done by PP-Y 5/3 $\times$ 2.5 mm^2 copper cable. Therefore, vertical propagation of the RCS through the distribution grid segment consisting of SS1–SS2 (T1–T2) line including described cabling has been measured.

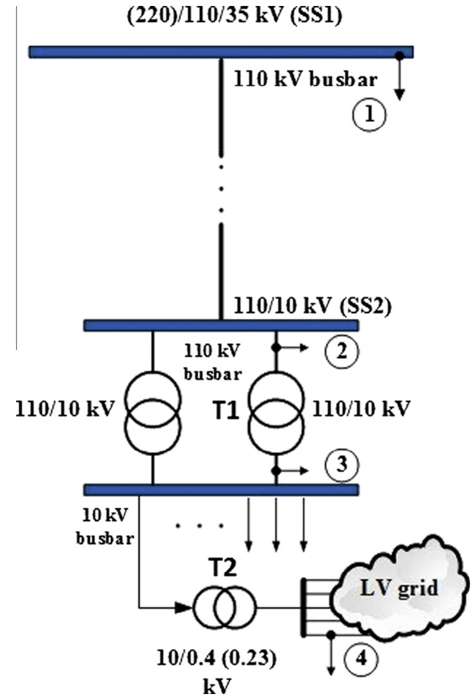

Fig. 1. RC signal vertical propagation measurement scheme. Number 1 denotes RCS injection point while numbers 2–4 denote measurement locations on different voltage levels.

The measurement of the RCS can be rather challenging task. Contrary to RC signal receivers [19], to the best of authors' knowledge, instruments capable of logging the Ripple Control Signal of the arbitrary injection frequency (within 110–3000 Hz interval), although commercially available are highly dependent on producers' national/local standards [20]. Additionally, since the magnitude of the injected signal is 2% of the nominal 50 Hz voltage level, signal to noise ratio, i.e. ratio of the ripple signal (at 208.3 Hz) and mains signal (at 50 Hz), is 1:50. This can be circumvented to a certain extent by considering the fact that RCS is the mains inter-harmonic of the given order, in our case 4th. [9]. Another issue arises from the fact that the RCS is only present during injection periods, which in this case means approximately 1 min, 9 times per day [21]. Considering the pulsed nature of the signal, this time – slot is effectively even shorter [1,14].

Keeping in mind previously stated measuring challenges, voltage pulse level meter in conjunction with Switched-Capacitor 10th order band-pass Butterworth filter was used. Aiming towards the best possible satisfaction of the Cardinal theorem of interpolation criteria [22], analogous upstream anti-aliasing filter of the 8th order has been added. Prior to measurements, filter properties were simulated and fine-tuned using FilterLab® to ensure central frequency of 208.3 Hz and bandwidth of 3.54 Hz, reducing squared amplitude of the Schottky and Johnson noise to negligible level.

The RCS measurements in the 3-phase system on 3 voltage levels, 110 kV, 10 kV and 400/230 V, respectively, have been performed. Since previously reported measurements [1,9], showed acceptable symmetry between phases, measured data obtained from phase A is taken to be representative. In case of 110 kV and 10 kV measurements, pulse voltmeter was connected in the