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S-parameters-based causal *RLGC(f)* model of busbar distribution systems for broadband power line communication

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ABSTRACT

Busbar power distribution systems are used extensively to carry energy as a noteworthy part of the low-voltage grid. In order to investigate the possibilities of a busbar system for low-voltage, broadband, power-line communication, the system is analyzed as a transmission line. For this purpose, S-parameter measurements at 1–50 MHz were conducted to represent the busbar using the frequency-dependent *RLGC(f)* model. The model's parameters were optimized with a two-step procedure to determine the optimal ranges of the parameters. To prove the causality of the busbar model, both time-domain and frequency-domain verifications were conducted. This points out that the model is causal and provides good agreement between simulated and measured S-parameters. The transfer characteristics of the busbar distribution network were taken out with the frequency-domain modeling approach by using the chain-scattering matrix method. The channel's performance under different network configurations, e.g., length, branch, and load, was investigated to provide a beneficial contribution for communication system designers.

1. Introduction

Power Line Communication (PLC) is a competitive communication technology that exploits the existing power cables for transmitting data. The power line network is the most widespread network, reaching every area where people live. However, this network is an excessively harsh medium for high-frequency communication signals, especially in the low-voltage (LV) grid. In addition to the cables used to transfer energy, LV grids also include busbar energy distribution systems to meet all of the power requirements, especially in industrial areas that have high power consumption. Since they are part of the LV grid, busbars should be examined in terms of PLC requirements [1,2]. It is clear that research related to PLC via power cables has not provided a complete and accurate identification of busbars. Therefore, as a PLC communication channel, the characteristics of the busbars' channels should be determined. The main objective of this study was to investigate and model the busbars in terms of PLC based on transmission line theory. Thus, PLC system designers will be aware of the busbar's characteristics as a part of the LV network.

When busbars are used to transmit high-frequency communication signals, they can be treated as transmission lines, and they can be represented with per-unit-length (p.u.l.) parameters [3,4]. Knowledge of the transmission line's behavior at the frequency band of interest is essential in creating an appropriate channel model. There are several reports that have examined the contributions of power lines and that have extracted the parameters of transmission lines, i.e., their p.u.l. parameters, i.e., their characteristic impedance (Z_c) and propagation constant (γ). The vast majority of them have been extracted based on measurements of the frequency-domain S-parameters [5–10]. Also, time-domain measurements are used to extract parameters [11–13]. Some researchers have presented a method for calculating the p.u.l. parameters over the measured Z_c and γ [5,10,14]. There are very few studies concerning the high frequency characteristics of busbars. The studies in Refs. [1,2] were simulation-based studies for busbar systems with copper conductors, and experimental validation should be conducted. Ref. [3] presented a simulation- and measurement-based study at the CENELEC and FCC bands.When the main focus is modeling the busbar as a transmission line, the most recent studies on the modeling of transmission lines may provide significant information. These are classified as conventional and modified methods [15–18], both of which use Vector Network Analyzer (VNA) measurements. In this study, the frequency-dependent *RLGC(f)* model was preferred because it can eliminate

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the discontinuities caused by the hyperbolic functions used to extract the parameters. Its results are more accurate, more precise, and more efficient [19–22]. The early modeling studies ignored the dielectric loss and the relationship between skin effect loss and $\sqrt{f}$ [23]. To compensate for the phase shift in the high frequency component of the total phase term in the transfer function, a non-linear phase term, $R_0/(2L\sqrt{\omega})$, is inserted. Thus, the skin effect loss model has been improved [23]. In [23,24], causality is a disadvantage because the dielectric loss is not taken into account. Thus, a new physical relaxation-based *RLC* model was developed that included both skin effect losses and dielectric losses [25]. Although [25] is a good step in terms of causality, in practice, obtaining the dielectric material's parameters for the relaxation model is very complex. Considering all of these shortcomings, the dielectric layer has been modelled using the two-term Debye model, and a frequency-dependent, causal *RLGC(f)* model is proposed [19–22]. In these studies, the extraction procedure involved using an optimization algorithm-based parameter. For the busbar systems, the first version of the *RLGC(f)* model was used to extract the parameters up to 500 kHz without causality enforcement [4].

The aim of this research was to model the busbar distribution system as a transmission line to obtain better information concerning the channel behaviors at the high-frequency band. After that, to show the behavior of the busbar as a PLC network in an LV grid, the transfer function for an N-branch busbar distribution network was derived by using the chain-scattering matrix method. The influence on the PLC network of the busbar's length, number of branches, and load impedance is shown.

2. Modeling a busbar and extraction of parameters

2.1. Busbar distribution system as a transmission line

Busbar energy distribution systems (Fig. 1) are used as part of an LV grid to conduct electricity where there is a high-current demand. It is a three phase system (L1, L2, L3) with a neutral (N), and such systems have different current carrying capacities, such as 630, 800, 1000, 1250, and 2000 A, depending on size [26].

As mentioned in Section 1, to provide an integrated communication medium for PLC, the busbar distribution system should be investigated for the point-of-communication possibilities as a part of the LV grid. For this purpose, the behavior of their transmission lines should be determined for the frequency band of interest.

Fig. 2 shows that transmission lines can be represented with an infinitesimal section of the transmission line (length of *dx*).

Telegrapher's equations, as given in (1) and (2), define an electrical signal traveling along a transmission cable.

$$\frac{\partial v(x,t)}{\partial x} + Ri(x,t) + L\frac{\partial i(x,t)}{\partial t} = 0 \tag{1}$$

$$\frac{\partial i(x,t)}{\partial x} + Gi(x,t) + C\frac{\partial v(x,t)}{\partial t} = 0 \tag{2}$$

Fig. 1. Example of a 630-A current level busbar (3-m length) [26].

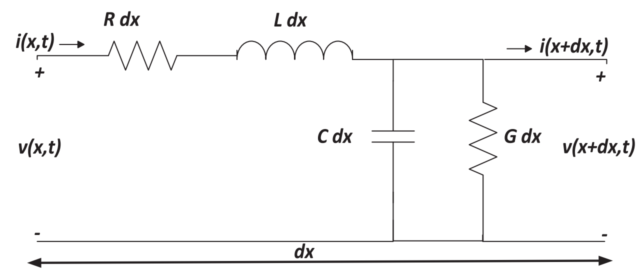

Fig. 2. Infinitesimal piece of transmission line.

If the p.u.l. parameters of a transmission line are known, the line's characteristic impedance (Z_c) and propagation constant (γ) can be calculated, as shown in (3) and (4), respectively.

$$Z_c = \sqrt{\frac{R(f) + j2\pi fL(f)}{G(f) + j2\pi fC(f)}} \tag{3}$$

$$\gamma = \sqrt{(R(f) + j2\pi fL(f))(G + j2\pi fC(f))} \tag{4}$$

To analyze the busbar as a transmission line, measurements were made of the S-parameters. The S-parameters define the relationship between a normalized incident wave and the reflected voltage wave. A three-phase busbar can be analyzed as six different two-port networks, i.e., L1-N, L2-N, L3-N (phase to neutral) and L2-L1, L3-L1, L3-L2 (phase to phase) [1–4]. Measurements of the S-parameters were made via MS2026 C Anritsu VNA Master for the six different two-port networks. Fig. 3 shows that the measurements were conducted separately in the 1–50 MHz frequency band. An M17/75-RG214-type coaxial cable with 50 Ω characteristic impedance was used for the connection between VNA and busbar. A two-port calibration was conducted to minimize the non-ideal effects caused by the measurement setup.

Calculation of the parameters of the transmission line for each measurement frequency produces erroneous values due to the effects caused by the port connections that cannot be included in the calibration step. For this reason, recent studies concerning the determination of RLGC values from measured S-parameters have proposed the use of a frequency-dependent transmission line model. In this study, the well-known *RLGC(f)* transmission line model [20] was used to obtain the line parameters of the busbar. A two-step optimization procedure was used in the search for the model's parameters. Using an optimization procedure to determine the unknowns instead of calculating them is more effective when measurement data are available (e.g., the S-parameters).

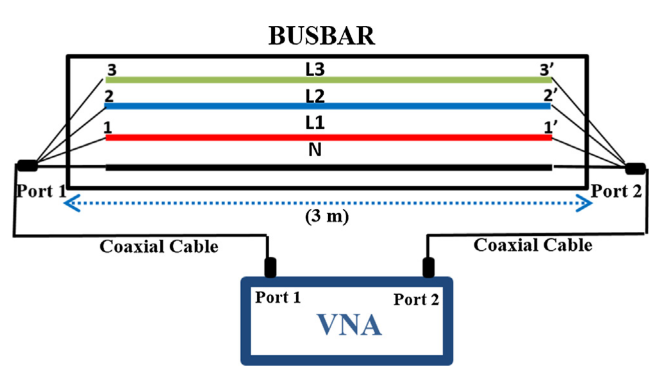

Fig. 3. Setup for measuring the S-parameters of the busbar.