# Input impedance of static power inverter of auxiliary drives of rolling stock according to UIC 550-3

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**Abstract** This paper focuses on the topic of the input impedance of static power inverters, which is a crucial parameter for controlling and regulating power inverters in rolling stock. The standard UIC 550-3 specifies the requirements for the input impedance of static power inverters used as auxiliary drives on rolling stock.

**Keywords** input impedance, UIC 550-3, power inverter

**JEL** L63, L69

## 1. Introduction

This paper deals about the input impedance of static power inverter is a critical parameter for control and regulation of power inverters in rolling stock. UIC 550-3 is the standard that specifies the input impedance requirements for static power inverters that are used as auxiliary drives on rolling stock. This document specifies that the input impedance of a static power inverter must meet certain criteria to ensure reliable operation and minimise power losses. In this article, we will discuss the importance of input impedance for static power inverters used as auxiliary drives for rolling stock according to UIC 550-3 and its impact on overall system efficiency.

## 2. Input impedance of the inverter

The input impedance of an inverter is given by the ratio of the input voltage of a given frequency that is injected to the DC signal to the current of a given frequency that the inverter draws. Zi(f) = Ui(f) / Ii(f) when the inverter is supplied with DC power. The UIC 550-3 standard prescribes the minimum impedance of an inverter for a particular frequency. Figure 1. shows a plot of the dependence of the required minimum input impedance (ZI) for a particular frequency. The graph shows that, for example, for a frequency of 50 Hz, the minimum required frequency is 80 Ω , Figure 1.

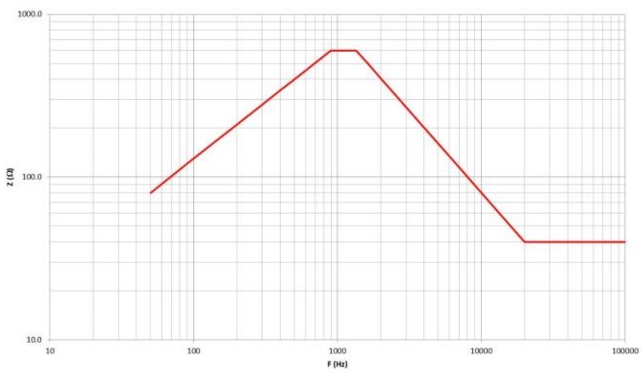


**Figure 1.** Dependence of the minimum required impedance of the converter for a particular frequency.

### 2.1. Inverter input impedance measurement technique

The input impedance (ZI) value was measured using the circuit shown in Figure 2. The input impedance was measured on a JN3029/400 high voltage inverter, which was configured as a JN3028 inverter. In the JN3029 inverter, the charger was disconnected from the intermediate circuit and the inverter was configured the same as in the JN3028 inverter. The auxiliary inverter was connected to the high voltage source A1. The injected voltage of the de-sired frequency was generated by the SN31-680/400 inverter. The total input current of the inverter, was measured using a current transducer. The AC component of the input current was measured using a Rogowski coil type Rocoil. The coil was connected to a Rocoil type integrator. The input voltage of the converter was measured using a high voltage probe. All measured voltages and currents were evaluated using the SIRIUS measurement system. The data from the SIRIUS measurement system was evaluated by the DAWEsoftX software running on a Lenovo laptop. The HV inverter was loaded with a three-phase inverter only. The inverter fed an asynchronous three-phase motor. The motor was connected to a dynamometer, which was used to load the motor with a constant torque of 100 Nm.

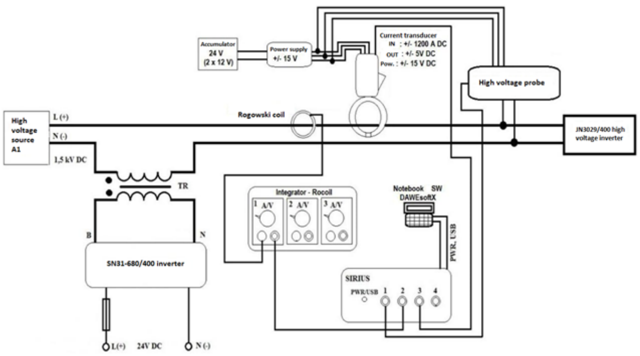


**Figure 2.** Block diagram of input impedance measurement of auxiliary converter JN3029.

The first step was to measure the impedance of the inverter without any intervention in the inverter hardware or software. The aim of the measurement was to find out what values of input impedance (ZI) the inverter achieves without modification of the control software. Figure 3. shows a plot of the dependence of the input impedance (ZI) on the frequency of the injected signal, where the limiting impedance values for each frequency are marked in red, the maximum measured values are marked in blue, and the minimum measured values are marked in brown.

From Figure 3. it can be seen that the input impedance of the converter is below the required limit in almost the entire frequency band of 40 Hz - 10 kHz. The impedance is above the limit only for injected frequencies above 3500 Hz, see Figure 3. The task of modifying the control program was to adjust the control of the high voltage (HV) converter so that the value of the input impedance (ZI) is always above the desired limit. The control method, including the necessary hardware modifications, is described in the following chapter.

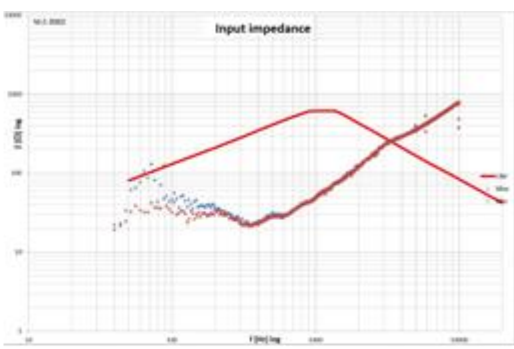


**Figure 3.** Dependence of input impedance on frequency of injected signal.

## 2.2. Inverter control method to increase the input impedance of the inverter

The standard control of a high voltage (HV) inverter consists of two main control members. The first is the D_shift controller, which determines the action of a given control member based on the voltage in the first intermediate circuit (Udc_ref1) and the input voltage Ui_shift. The second control member is a pair of PI controllers connected in series. The first PI controller determines the reference value of the input current based on the actual and the desired value of the second intermediate circuit. The second PI controller, based on the given reference and actual input current, calculates an action for the given control member. The action hits from the two members are summed and the result is fed to the PWM modulation input. The resulting pulses from the PWM block directly drive the individual IGBT control transistors of the inverter. A schematic of the inverter control, without input impedance (ZI) compensation, is shown in Figure 4.

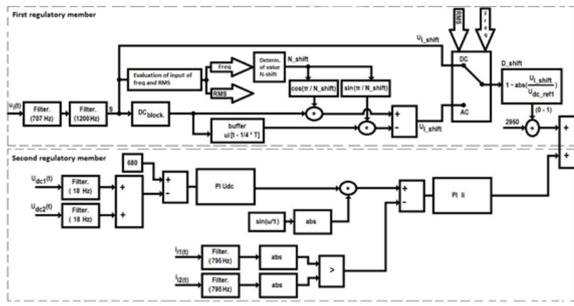


**Figure 4.** Schematic of inverter control without input impedance compensation.

The modification of the control of the HV converter consisted of modification of the control software and hardware modification of the analogue input board. It was necessary to replace the filter capacitor on the analog input board, on the AI0 input. The originally fitted capacitor with a capacitance of 4.4 μF was replaced with a capacitor with a capacitance of 470 nF. The reason for the replacement was the need to evaluate the injected signal up to a frequency of 5000 Hz. The originally fitted capacitor caused a high attenuation of the amplitude of the injected signal already at a frequency of about 850 Hz. The modification of the control software consisted of two main steps. The first step was the modification of the Ui_shift signal generation. The AC (injected) component of the DC signal undergoes the signal adjustment. It was first necessary to extract the AC (injected) portion of the input voltage from the signal, thus obtaining a signal that contains only the AC (injected) component of the input voltage. The frequency and the effective value are then determined from the signal. Based on the data obtained, the amplitude of the signal is changed and the signal is shifted along the time axis. The effective value of the input voltage is added to the signal thus modified.

The resulting signal is then the Ui_shift signal, which is applied to the D_shift input of the controller. See. Figure 5. Block diagram of the inverter control in the case of active input impedance (ZI) increase. The second step is to add a controller for the AC component of the input current. In this case, it is a PI controller that modifies the control so that the AC component of the input current is zero. Similar to the signal conditioning for the D_shift controller, the AC component of the input current must first be obtained. The given signal is then applied to the input of the PI controller where the desired value for the given signal is zero. Unlike the D_shift controller, which operates over the entire frequency range of the input injected signal (40 - 5000 Hz), the given PI controller operates only when the frequency of the injected signal is less than 700 Hz. Figure 5. shows a block diagram of the inverter control in the case of active input impedance (ZI) increase. The above modifications represent a third control term, which is active only in the case of a DC voltage at the inverter input and only if the program detects an injected voltage at the inverter input. Figure 6. shows a schematic of the control with the above third control element, which is divided into two parts.

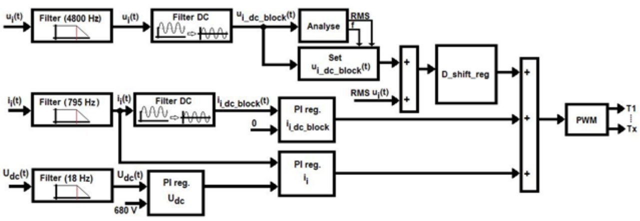


**Figure 5.** Block diagram of inverter control in case of active input impedance increase.

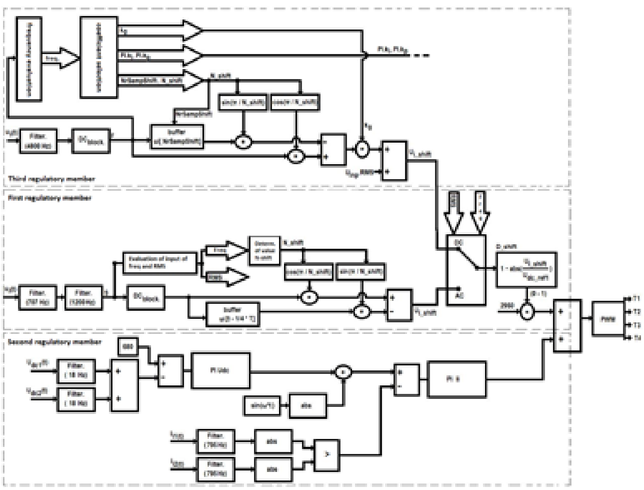


**Figure 6.** Schematic of inverter control in case of active input impedance increase.

As shown in Figure 6 the control program of the HV converter varies the parameters k0 - gain of the injected signal, kp - PI controller parameters of the zero ac component of the input current (ki = 0.015 for all frequencies of the injected signal), N_shift - the shift parameter of the injected signal along the time axis, and NrSampleShift, according to the frequency of the injected signal where : NrSampleShift = ¼ of the period of the injected signal converted to the number of samples. The correct values of the above parameters were obtained experimentally for each frequency. The obtained results, including the minimum and maximum impedance values for each frequency will be presented in the next section.

## 2.3. Measurement Results

Experimental results k0 - gain of injected signal, kp - parameters of PI controller of zero alternating component of input current, N_shift - parameter of shift of injected signal along the time axis proceeded as follows. The diagnostic program of the HV inverter allowed to change individual parameters. The input impedance was measured according to the circuit shown in Figure 2 and the value was available immediately when the parameters were changed. By the given procedure it was possible to detect immediately the influence of the change of individual parameters on the input impedance. During the experiments, the value of only one of the parameters was changed each time and the effect of the coefficient on the input impedance (ZI) value was evaluated based on the input impedance (ZI) measurement. The experiment was terminated when the input impedance (ZI) was reduced by changing the parameter. A summary of the results of the above parameters for each frequency is given in Table 1. Table 1 also shows the results of the minimum and maximum impedance.

**Table 1.** Summary of results of individual parameters for each frequency.

| $U_{input}$ [Hz] | $k_0$ [] | N_shift [] | Kp [] | ZI min [Ω] | ZI max [Ω] | Limit ZI [Ω] |
|---|---|---|---|---|---|---|
| 50 | 1,05 | 1,667 | 85 | 127 | 132 | 80 |
| 75 | 1,05 | 1,667 | 85 | 203 | 215 | 106,1 |
| 100 | 1,328 | 1,667 | 84,9 | 386 | 429 | 129,7 |
| 200 | 1,250 | 1,148 | 75,0 | 1416 | 4547 | 210,3 |
| 300 | 1,250 | 0,179 | 75,0 | 1287 | 12737 | 279 |
| 400 | 1,250 | 0,140 | 75 | 779 | 1874 | 340,9 |
| 500 | 1,119 | 0,125 | 74,9 | 903 | 2302 | 398,3 |
| 600 | 1,15 | 0,120 | 1,0 | 940 | 4049 | 452,3 |
| 700 | 1,149 | 0,119 | 1,0 | 652 | 3671 | 503,6 |
| 800 | 1,099 | 0,115 | 1,0 | 690 | 1964 | 552,7 |
| 900 | 1,019 | 0,115 | 1,0 | 2877 | 32994 | 600 |
| 1000 | 1,0 | 0,115 | 1,0 | 1350 | 3796 | 600 |
| 1100 | 0,998 | 0,121 | 1,0 | 1402 | 2730 | 600 |
| 1200 | 0,850 | 0,110 | 1,0 | 3339 | 4957 | 600 |
| 1300 | 0,851 | 0,1160 | 1,0 | 1285 | 1650 | 600 |
| 1400 | 0,722 | 0,1079 | 1,0 | 1513 | 2116 | 578,5 |
| 1500 | 0,709 | 0,1141 | 1,0 | 591 | 3193 | 539,7 |
| 1600 | 0,580 | 0,115 | 1,0 | 3565 | 3698 | 505,9 |
| 1700 | 0,500 | 0,107 | 1,0 | 3740 | 5538 | 476 |
| 1900 | 0,307 | 0,113 | 1,0 | 3162 | 5520 | 425,6 |
| 2100 | 0,167 | 0,0939 | 1,0 | 9233 | 98123 | 384,9 |
| 2300 | 0,05 | 0,0682 | 1,0 | 3663 | 5225 | 351,3 |
| 2600 | 0,197 | 0,04900 | 1,0 | 5045 | 22387 | 310,6 |
| 3100 | 0,897 | 0,0483 | 1,0 | 623 | 1002 | 260,3 |
| 4000 | 4,55 | 0,0565 | 1,0 | 246 | 312 | 201,5 |

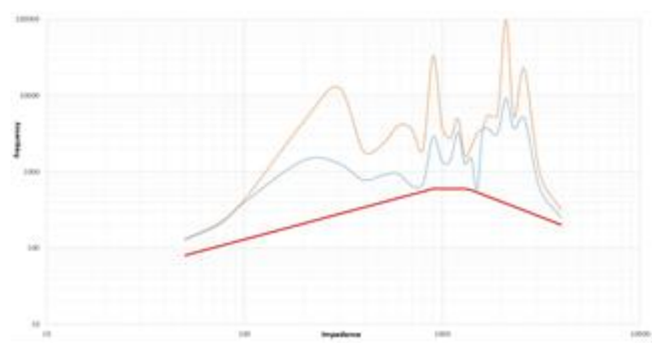

**Figure 7.** Dependence of the minimum and maximum input impedance on the frequency of the injected signal.

Figure 7 shows a summary of the results achieved. The red waveform represents the limiting values of the input impedance for each frequency. The blue waveform represents a summary of the minimum input impedance values that were measured in the experiments with the set parameters for each frequency. The brown waveform represents the sum of the maximum input impedance values that were measured in the experiments with the set parameters for each frequency. From Figure 7, it can be seen that the achieved input impedance values, for the individual frequencies, are above the required limits for the individual frequencies. The highest input impedance was measured when the frequency of the injected signal was 2100 Hz whereas the closest to the allowed limit was the input impedance when the frequency of the injected signal was 4000 Hz (44.5 Ω above the limit).

All experiments were performed at one input voltage level, approx. 1550 V and one loaded HV inverter, the inverter input current Ii approx. 13A. For the injected signal frequencies of 50 Hz, 75 Hz,100 Hz, 200 Hz and 3100 Hz, the effect of load variation on the input impedance was also experimentally measured so that the input impedance was measured with the same parameter set at three different loads. The results of the given measurements are shown in Table 2, 3, 4, 5 and 6. Where Ii is the effective value of the input current and the note shows the value of the motor load that was connected to the inverter.

**Table 2.** Measurement of the effect of load variation on the input impedance of the inverter for Uinject = 50 Hz.

| $k_u$ [] | N_shift [] | $k_p$ [] | ZI min [?] | ZI max [?] | $I_i$ [A] | Poznámka |
|---|---|---|---|---|---|---|
| 1,05 | 1,667 | 85 | 126 | 132 | 10,3 | 50 Nm |
| 1,05 | 1,667 | 85 | 127 | 132 | 14,0 | 100 Nm |
| 1,05 | 1,667 | 85 | 118 | 124 | 19,6 | 150 Nm |

**Table 3.** Measurement of the effect of load variation on the input impedance of the converter for Uinject = 75 Hz 3. Page Style

| $k_u$ [] | N_shift [] | $k_p$ [] | ZI min [Ω] | ZI max [Ω] | $I_i$ [A] | Poznámka |
|---|---|---|---|---|---|---|
| 1,050 | 1,6668 | 85 | 220 | 231 | 8,9 | 50 Nm |
| 1,050 | 1,667 | 85 | 203 | 215 | 13,8 | 100 Nm |
| 1,05 | 1,6674 | 85 | 180 | 190 | 19,7 | 150 Nm |

**Table 4.** Measurement of the effect of load variation on the input impedance of the converter for Uinject = 100 Hz.

| $k_u$ [] | N_shift [] | $k_p$ [] | ZI min [Ω] | ZI max [Ω] | $I_i$ [A] | Poznámka |
|---|---|---|---|---|---|---|
| 1,328 | 1,6674 | 84,9 | 298 | 322 | 8,5 | 50 Nm |
| 1,328 | 1,6675 | 84,9 | 396 | 429 | 13,5 | 100 Nm |
| 1,328 | 1,6672 | 84,9 | 371 | 417 | 19,3 | 150 Nm |

**Table 5.** Measurement of the effect of load variation on the input impedance of the converter for Uinject = 200 Hz.

| $k_u$ [] | N_shift [] | $k_p$ [] | ZI min [Ω] | ZI max [Ω] | $I_i$ [A] | Poznámka |
|---|---|---|---|---|---|---|
| 1,250 | 1,1486 | 74,9 | 561 | 805 | 8,9 | 50 Nm |
| 1,249 | 1,1500 | 74,9 | 982 | 1654 | 12,5 | 100 Nm |
| 1,2490 | 1,1489 | 74,9 | 795 | 1559 | 19,0 | 150 Nm |

**Table 6.** Measurement of the effect of load variation on the input impedance of the converter for Uinject = 3100 Hz

| $k_u$ [] | N_shift [] | $k_p$ [] | ZI min [Ω] | ZI max [Ω] | $I_i$ [A] | Poznámka |
|---|---|---|---|---|---|---|
| 0,9 | 0,04820 | 1,0 | 274 | 327 | 8,5 | 50 Nm |
| 0,9 | 0,04820 | 1,0 | 623 | 1002 | 13,5 | 100 Nm |
| 0,9 | 0,04820 | 1,0 | 575 | 781 | 19,3 | 150 Nm |

The effect of load variation on the input impedance for the other frequencies has not been investigated. The load for the remaining frequencies was about 13 A of input current. The motor connected to the inverter was always loaded with a torque of 100 Nm. Also, the impedance was not measured if the injected signal had a frequency outside the value given in Table 1. The given experiments were not performed due to their high time requirement. Example: Frequencies in the range 50-4000 Hz in steps of 5 Hz at 5 load levels will give a total of 3950 experimental measurements. Which with a time requirement of approx. 1 hour per measurement is 3950 hours = approx. 526 working days = approx. 24 months of work on experimental measurements alone.

# 3. Conclusions

As presented in the previous chapter, by actively controlling the input impedance, it was possible to increase the input impedance of the HV converter above the required limit. All the experiments of changing the coefficients, as described in the previous chapter, were performed only for the frequencies listed in Table 1. If the frequency of the injected signal is between the values in Table 1, the values for that frequency are calculated by selecting the next higher value and the next lower value from Table 1 and fitting a straight line through the given parameters. In other words, the next higher value and the next lower value are used for the linear substitution. The given procedure is used to determine the coefficients "a" and "b" of the formula "y = a*x+b", where "x" is the input frequency of the injected signal and "y" is the value of the parameter we need to determine. The control program of the HV inverter has been modified according to the results and is archived as version R000067_02 for the needs of the JN3028.x inverter.

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# REFERENCES


[1] Biel, Z.: VS20190429 Input impedance of the inverter; Measurement of the influence of changes in the SW of the HV inverter on the input impedance, Ele. EVPÚ, a. s. archive;05/2017

[2] Kácsor, G.: VS20190429 Input impedance converter. Increasing input impedance of auxiliary converters. Effect of inverter circuit components on input impedance. Ele. EVPÚ, a. s. archive;10/2018

[3] SKTC: 2019-00035T. Test report No. 0-0035T/2019. Input impedance.

[4] Ahmed, K.H. & Finney, S.J. & Williams, B.W.. (2007). Passive Filter Design for Three-Phase Inverter Interfacing in Distributed Generation. 1 - 9. 10.1109/CPE.2007.4296511.

[5] K. Takacs and M. Frivaldsky, "Simulation design of residential smart-grid based on solid-state transformer," 2022 ELEKTRO (ELEKTRO), 2022, pp. 1-6, doi: 10.1109/ELEKTRO53996.2022.9803792.

[6] M. Prodanovic and T. C. Green, "Control and filter design of three-phase inverters for high power quality grid connection," in IEEE Transactions on Power Electronics, vol. 18, no. 1, pp. 373-380, Jan. 2003, doi: 10.1109/TPEL.2002.807166.

[7] M. Schweizer and J. W. Kolar, “Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications,” in IEEE Transactions on Power Electronics, vol. 28, no. 2, pp. 899-907, Feb. 2013

[8] R. Teodorescu, M. Liserre and P. Rodriguez, “Grid converters for photovoltaic and wind power systems”, pp. 289-311, IEEE, Wiley, 2011.

[9] Behrouzian, Ehsan. (2016). Operation and control of cascaded H-bridge converter for STATCOM application: https://www.researchgate.net/publication/301349487_Operation_and_control_of_ cascaded_H-bridge_converter_for_STATCOM_application

[10] Jost Allmeling, Niklaus Felderer “Sub-cycle average models with integrated diodes for real-time simulation of power converters”, 2017 IEEE Southern Power Electronics Conference (SPEC), pp. 1-6, 2017