IMPEDANCE OF INVERTER FRONT-ENDS AT THE FREQUENCY OF RIPPLE-CONTROL SIGNALS

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ABSTRACT

Ripple control is the technique of controlling loads and other devices in the distribution grid by sending low-frequency signals along the phase conductors or the neutral conductor. The magnitude of the signal is determined by the impedance of the network, loads, capacitor banks, filters and generators. An increase of the amount of electrical equipment connected to the grid, e.g. due to an increasing use of distributed generation, changes the impedance of the power system. This can cause excessive amplification or attenuation of the control signals, resulting in the malfunction of receivers and other equipment. In this paper, the impedance of three-phase inverter front-ends at the frequency of the control signals is discussed. The following elements are taken into account: The AC filter, the switching of the inverter and the DC circuit. Equivalent impedances are calculated, which can be used in analytical calculations.

INTRODUCTION

Ripple control is the technique of controlling loads and other devices in the distribution grid by sending signals along the conductors. It is one-way communication, from a central transmitter to a large number of receivers (multicasting). A sinusoidal voltage with a certain frequency is used to broadcast a series of bits by means of on/off modulation. The signal waveform is a three-phase, symmetrical voltage, with a magnitude of about 1 to 5 % of the grid's rated voltage and a frequency between 125 and 3000 Hz, usually an interharmonic. The duration of one broadcast can range from a few seconds to a few minutes.

Typical applications are tariff switching, control of energy meters, synchronization of devices, control of public lighting, control of infrastructure of distribution grids, switching customers' loads and load shedding. 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 [1], [2].

The magnitude of the signal as detected by the receivers is determined by the impedance of the network and the systems connected to the network, such as loads, capacitor banks, filters and generators. An increase of the power installed, e.g. due to the increasing use of distributed generation, can cause excessive attenuation or amplification of the signals [3], [4]. Attenuation can result in signals not being detected by receivers [5]. Amplification can result in flicker [2]. In this paper, the impedance of inverter (or converter) front-ends at the signal frequency is discussed. This is a relevant subject because inverters are an important tool in the field of distributed generation (e.g. photovoltaic systems and microturbines). They are also applied in many loads such as drives, especially with the aim of rational use of electrical energy.

The inverter type used here is the three-phase voltage-source inverter, using pulse-width modulation (PWM) to generate an output voltage with low harmonic content [6]. The following elements are taken into account: The AC filter (a series inductor), the switching sequence of the inverter and the DC circuit. The propagation of the signal waveform trough these elements is simulated.

Using the fast Fourier transform (FFT), equivalent impedances are derived from the relation between the signal voltage and the component of the current at the same frequency. A converter can then be replaced by the Y connection of these impedances. This is useful when doing analytical calculations concerning the effect of inverters on the transmission of ripple-control signals in actual cases.

DESCRIPTION OF THE SYSTEM

The system under consideration is shown in figure 1. It consists of a three-phase inverter, a DC circuit (on the left) and an AC circuit (on the right). The DC circuit consists of a power source and a filter. In order to limit the complexity of the model, the power source is modelled as a DC voltage source U_{DC} with an internal resistance R_{DC}. This is an accurate model if the power source is an array of batteries, e.g. in a storage system. For other types of power sources, such as photovoltaic modules with a DC/DC converter, this is a simplified model.

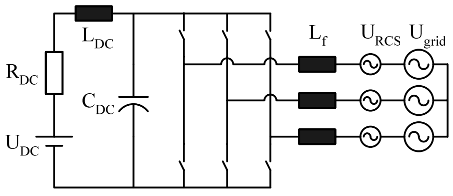

Figure 1 Inverter connecting the DC source to the three-phase grid with superimposed ripple-control voltage (U_{RCS}).

The other elements of the DC circuit make up a filter: a series inductor L_{DC} and a shunt capacitor C_{DC}. The AC circuit consists of a three-phase symmetrical voltage source U_{grid} (400 V, 50 Hz) and three inductors L_f for power injection and filtering of the injected current.

Because our purpose is to study this system when voltages at signal frequency are applied, sources at other frequencies, including U_{DC} and U_{grid}, are not taken into account during simulation of this system. These sources are replaced by short circuits, resulting in the system shown in figure 2a. In reality, the ripple-control signal (U_{RCS}) is superimposed on the fundamental voltage, and the waveform appearing on the DC side as a result of the signal is superimposed on the DC voltage.

Figure 2b shows the system with the inverter and the DC circuit replaced by three equivalent impedances Z_{eq} (= R_{eq} + j X_{eq}). Determining Z_{eq} is the goal of the work presented here. Before achieving this, the system model has to be programmed and parameter values are required. In the next paragraphs, the simulated mechanism is described and the choice and calculation of suitable values for the parameters of the system are discussed. Examples of parameter values are listed in table 2 in the appendix.

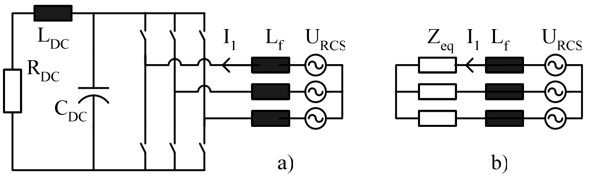

Figure 2 a) Simulated system: inverter without DC source and grid voltage. b) Inverter and DC circuit replaced by the equivalent impedance Z_{eq}.

Simulated mechanism

Ripple-control signals appear at the terminals of the inverter. When the inverter's semiconductor switches are conducting, the signal voltage appears on the DC side. The switching sequence results in the three AC phases being connected alternately to the positive and the negative pole of the DC circuit. Because of this, the voltage appearing across the DC circuit is a sequence of fragments of the three signal waveforms, distorted by the voltage drop across the inductive AC filter.

The result of the voltage on the DC side is current flowing through both parallel branches of the DC circuit. The sum of both currents is the total current. An example of this waveform is shown in figure 3. This waveform consists of a sequence of fragments of sinusoidal waves, related to the three-phase signal voltage. The total current is distributed over the three AC phases. The signal current on the AC side is a sine wave at signal frequency, with a few weak components at other frequencies.

Inverter parameters

The main parameter of the inverter is its rated power. For the simulations, four values are used: 5 kW, 20 kW, 80 kW and 320 kW. Four values are considered for the frequency f_{PWM} of the triangular waveform of the PWM-signal generator: 5250 Hz, 10050 Hz, 15150 Hz and 20250 Hz. At these frequencies an uneven number of half periods of the triangular waveform fit inside one half period of 50 Hz, resulting in a symmetrical, periodic PWM waveform. The switching elements are assumed to be ideal (zero resistance).

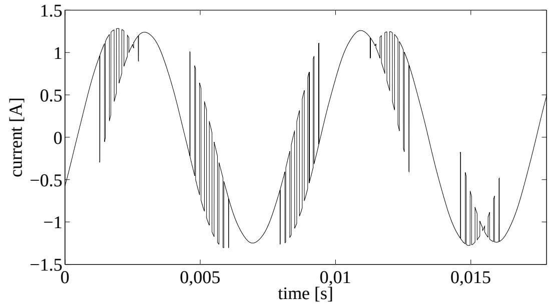

Figure 3 Current through the DC circuit of a 20 kW converter (f_{PWM} = 5250 Hz, m_a = 4, f_{RCS} = 167 Hz).

Parameters of the DC circuit

The circuit on the DC side of the inverter consists of a voltage source and a filter. For the calculation of the series resistance R_{DC} of the source, values of the internal resistance of lead-acid batteries are used. The battery array is dimensioned in order for the inverter to inject its rated power in the AC grid for a period of 5 hours. For the DC voltage 660 V is chosen, resulting in an output line voltage of 400 V (i.e. the rms value of the fundamental component) when the amplitude-modulation ratio m_a is 1 [6].

The DC filter circuit is required to reduce the current ripple which results from PWM during power generation. For the filter circuit, two possibilities are considered. The first possibility is to use only the shunt capacitor (L_{DC} = 0 H). In this case the capacitor is dimensioned to obtain an attenuation of the current ripple at the PWM frequency by a factor two.

The second possibility consists of the combination of the shunt capacitor C_{DC} and the series inductor L_{DC}. With the addition of the inductor, higher attenuation of the PWM ripple can be obtained using a smaller capacitor, compared to the first possibility. Here the capacitance is chosen to be ten times smaller than the capacitance of the first possibility. Next, the inductor is dimensioned so as to obtain attenuation by a factor ten at the PWM frequency.

Parameters of the AC circuit

The AC terminals of the inverter are connected to the grid by means of inductors or a three-phase transformer. The active power transferred through the inductor depends on the fundamental component of the inverter's output voltage (magnitude and phase) and the inductors L_f. These inductors are also filters, limiting the harmonic content of the output current.

For each power rating a value for the filter inductor is required. This is derived from the rated inductor voltage and the power to be transferred. The value chosen for the rated voltage across the inductor is the difference between the maximum output voltage (phase voltage, at square-wave operation) and the phase voltage of the grid, when both voltages are in phase. This voltage is 66 V.

Simulation and calculation

In order to have maximum control of the simulation, the model is programmed with Matlab. Because an FFT is used in the calculations, the number of simulation points is chosen to be a power of two. The time step between consecutive points has to be constant. The simulation period is one second, resulting in a frequency resolution of 1 Hz for the frequency spectrum.

A simulation results in a time sequence for the current in one of the three phases (I_1 in figure 2a). From the FFT of this series, the (complex) value at the signal frequency is selected. The magnitude of the signal voltage is divided by the selected value, resulting in an impedance with a complex value. Because the inverter is connected to the signal source by means of the filter inductors L_f, the reactance of one inductor (jX_f) has to be subtracted from the calculated impedance. This yields the equivalent impedance Z_{eq} of the inverter front-end and its DC circuit. A Y connection of three times this impedance in series with jX_f can then be used as a model of the inverter at signal frequency.

DISCUSSION OF RESULTS

With the parameter values discussed before, simulations are conducted. In these simulations, the following signal frequencies are used: 167, 383, 750 and 1350 Hz, the first and the last frequency being the lowest and highest signal frequency used in Germany [1].

Inverter with C filter

For inverters with a C filter in the DC circuit, the equivalent impedance Z_{eq} is small: less than 1 % of the impedance of the inductive AC filter. The combination of low resistance of the source and the shunt capacitor results in low impedance for the various frequencies present in the voltage at the DC side. Z_{eq} increases with increasing modulation ratio m_a. It does not depend on f_{PWM}. Inverters with a higher power rating have a lower Z_{eq}.

X_{eq} is negative; therefore the combination of the inverter and the DC circuit is capacitive. In calculations concerning the transmission of ripple-control signals, these inverters, including the AC filter L_f, can be represented by the Y connection of the three filter inductors, neglecting Z_{eq}.

Inverter with LC filter

For inverters with an LC filter, Z_{eq} is higher than for inverters with a C filter. This is due to the smaller capacitance and the addition of an inductor. In the signal-frequency range up to 1350 Hz, Z_{eq} is inductive. The equivalent resistance and inductance are increased when the PWM frequency is decreased. The resistance and the inductance are increased when the amplitude modulation ratio is increased, resulting in maximum resistance and inductance at square-wave operation of the inverter. Inverters with a higher power rating have lower equivalent impedance. R_{eq} and X_{eq} decrease with increasing PWM frequency. The ratio of impedance for f_{PWM} = 5250 Hz to impedance for f_{PWM} = 20250 Hz is about 3.7 at 167 Hz signal frequency and it is 11 at 1350 Hz. In table 1 it is shown how Z_{eq} compares to the impedance of the AC filter L_f. For f_{RCS} equal to 1350 Hz, the contribution of the inverter to the overall impedance of the system is largest.

Table 1 Ratio (in %) of maximum values of Z_{eq} to Z_f (ωL_f) for 4 power ratings and 4 signal frequencies, for inverters with LC filter

	5 kW	20 kW	80 kW	320 kW
167 Hz	2.0 %	2.0 %	1.8 %	1.3 %
383 Hz	1.9 %	1.9 %	1.7 %	1.3 %
750 Hz	2.4 %	2.4 %	2.2 %	1.6 %
1350 Hz	6.0 %	6.0 %	5.2 %	4.0 %

Based on an additional series of simulations, the impedance of a 20 kW inverter and its DC circuit was calculated for frequencies up to 2000 Hz. The imaginary part of this impedance is shown in figure 4 (solid lines), for three values of the modulation ratio m_a: 0.5, 1 and 4. With $m_a = 4$ (strong overmodulation), the inverter is not yet generating a square-wave output voltage, but the impedance is about the same.

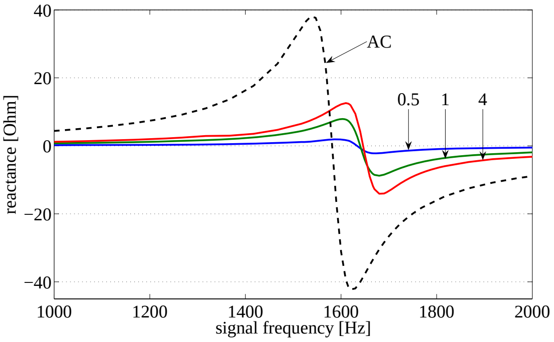

Figure 4 Equivalent reactance of the 20 kW inverter (f_{PWM} = 5250 Hz) as a function of signal frequency for modulation ratios 0.5, 1 and 4. Dashed line: reactance of the DC circuit.

In this figure it is shown that the magnitude of the equivalent reactance increases with a higher modulation ratio. The same is true for the equivalent resistance. The explanation for this is that the shape of the current waveform through the DC circuit resembles the signal waveform more closely as square-wave operation is approached, as can be seen in figure 3. As m_a is increased, the switching periods between the longer sine fragments become shorter. At lower modulation ratios, stronger high-frequency components are present at the DC side, for which the DC capacitor is a low impedance, resulting in higher current and thus lower impedance.

The reactances in figure 4 have a resonance point at about 1640 Hz. For frequencies below 1640 Hz, the reactance is positive (or inductive). For higher frequencies, it is negative (or capacitive). The real part of the impedance also shows resonance at this frequency. For $m_a = 4$, the resistance is 28 Ω at this frequency. The impedance X_f of the AC filter is 75 Ω at this frequency. The total reactance and resistance for the 20 kW inverter are shown in figure 5.

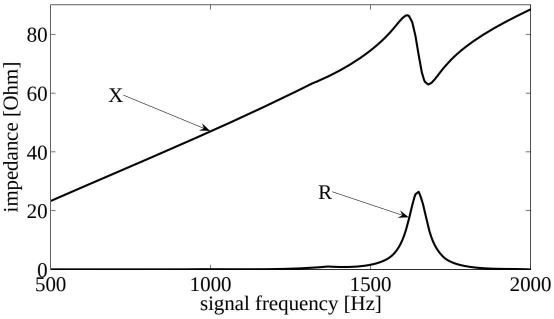

Figure 5 Total reactance and resistance of the combination of the AC filter, the inverter and the DC circuit ($P = 20$ kW, $m_a = 4$, $f_{PWM} = 5250$ Hz)

If the equivalent reactance is compared to the general AC reactance of the DC circuit, which is the dashed line in figure 4, it is found that the impedance characteristic of the inverter with the DC circuit resembles that of the DC circuit. There is a difference of about 50 Hz between their respective resonance frequencies. The explanation for this shift is that the strongest frequency on the DC side is 50 Hz lower than the signal frequency. This is observed for all values for f_{PWM} and f_{RCS}. This is illustrated in figure 3, where the result of successive phase-shifted sine fragments is a fundamental wave with a lower frequency. When this frequency is equal to the resonance frequency of the inverter, the resonance point shows up 50 Hz higher on the AC side.

Because the frequency characteristic of the equivalent impedance is a scaled and shifted version of impedance of the DC circuit, a simple, frequency-dependent model can be easily implemented in analytical calculations concerning ripple-control calculations.

For systems equipped with a shunt capacitor on the AC side in addition to the inductor L_f, for additional harmonic filtering, the total impedance is the parallel circuit of this capacitor and the series circuit of the inductance and the equivalent impedance of the inverter and the DC circuit.

CONCLUSIONS

The impedance of three-phase inverter front-ends has been investigated for frequencies used in ripple control. The results can be used in power-system analysis concerning the transmission of control signals in distribution grids. The following elements have been taken into consideration: the inductive AC filter, the inverter (with PWM) and the DC circuit, consisting of a filter and a DC power source. The power source has been modelled as a voltage source with internal resistance.

The results indicate that the impedance of the inverter and the DC circuit (i.e. without the AC filter) as a function of signal frequency is similar in shape to the AC impedance of the DC circuit, except that it is shifted towards higher frequencies by about 50 Hz and that the magnitude depends on the inverter's modulation ratio and switching frequency.

APPENDIX

Table 2 System parameters for a 20 kW and an 80 kW inverter. The values for C_{DC} and L_{DC} depend on the PWM frequency.

Rated power of inverter:			20 kW	80 kW
C filter	L_{DC} [H]		0	0
	C_{DC} [μF]	5250 Hz	238.7	997.2
		10050 Hz	124.7	520.8
		15150 Hz	82.7	345.7
		20250 Hz	61.9	258.7
LC filter	L_{DC} [μH]	5250 Hz	423.2	101.3
		10050 Hz	221.1	52.9
		15150 Hz	146.8	35.1
		20250 Hz	109.8	26.2
	C_{DC} [μF]	5250 Hz	23.9	99.7
		10050 Hz	12.5	52.1
		15150 Hz	8.3	34.6
		20250 Hz	6.2	25.9
DC source	R_{DC} [mΩ]		220	52.6
AC filter	Lf [mH]		7.30	1.82

ACKNOWLEDGMENTS

This work is supported by the Belgian "Fonds voor Wetenschappelijk Onderzoek - Vlaanderen" and Eandis (Belgian distribution system operator).

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